Front End Analysis
of Mobile Electric Power
Research and Development
for the 2015-2025 Time Frame

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Executive Summary

Background

Advanced warfighting capabilities rely on electric power. It is the lifeblood of the modern digitized battlefield. TRADOC envisions a need to have sustained tactical electric power for a minimum of 72 hours without human interface for logistics resupply in the 2015-2025 time frame. This Front End Analysis (FEA) is one effort on the path to realizing this requirement.

History

US Army Training and Doctrine Command (TRADOC) and the US Army Materiel Command (AMC) have identified a requirement to develop a mobile electric power roadmap. In 2001, TRADOC, CECOM, and the US Army Combined Arms Support Command (CASCOM) jointly developed a TRADOC Vision Statement for Mobile Electric Power Research and Development for the 2015-2025 Time Frame. The US Army Communications-Electronics Command (CECOM) subsequently identified a need to conduct a FEA of power generation technology. This FEA follows from that Vision Statement, providing guidance for developing future mobile electric power.

Approach

The objective of this FEA is to provide guidance for a mobile electric power roadmap, as requested by TRADOC. The FEA investigates available technologies for mobile electric power generation and energy storage. It also considers performance enhancements common to a number of power technologies and identifies information technologies that may be adapted to enhance tactical mobile electric power.

Scope

This FEA, conducted from December 2001 to June 2002, covers the requirements, constraints, and applicable technologies for making the greatest progress toward realizing the TRADOC’s vision of mobile electric power.

Strategy

This FEA considers various electric power generation technologies, energy storage devices, energy conversion mechanisms, methods of performance enhancement of the various generation and storage technologies, and relevant information technologies. This FEA draws upon achievements and advances in mobile electric power and related technology from the Army, the other Services, other government agencies, academia, and industry. For each technology, an appropriate state-of-the-art is identified, including expectations for the 2015-2025 time frame. Force design principles provide a context for developing a number of criteria to analyze the suitability of adopting each technology. This gives insight into the relative strengths and weaknesses of each technology.

Conclusion

This FEA determines that a fuel-driven engine, either internal combustion or turbine, is the most desirable approach for achieving a 72-hours of tactical mobile electric power without human interface. Advancements in information technology hold great potential for transforming tactical mobile electric power just as they will transform the force in general. Effective power management will be essential to realizing the 72-hour goal.

Recommendations

- Place the most emphasis on internal combustion engine and microturbine. These technologies work best today. Significant further technological advancement will keep them far ahead for the next twenty years.
- Continue to monitor fuel cell and commercial hydrogen distribution and storage systems. Practical hydrogen fuel cells already exist, but acceptable methods of hydrogen distribution and storage may not be available by 2015. Reformed methanol fuel cells will be commercially available long before 2015 and one using gasoline is likely. A fuel cell using tactical fuels is not likely. Be able to quickly leverage any breakthroughs if they occur.
- Energy storage should employ chemical batteries combined with capacitors in hybrid configurations.
- Apply information technology enhancements to improve operation, maintenance, and decision-making. Just as information technology is transforming the soldier system, so it must transform tactical mobile electric power generation if we are to remain competitive.
- Designate a fully resourced power management office with total responsibility for power management policy and implementation. Power management is a vehicle for effectively integrating new technologies and for gaining and retaining control of power demands, both in design and in operation.
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Section I

Introduction

Purpose
This Front End Analysis (FEA) of mobile electric power for the 2015-2025 time frame investigates the technologies available to provide for mobile electric power requirements in the 500 Watt to 10 kW range. It assesses available mobile electric power technologies that are applicable to a solution, including energy storage methods. A number of significant performance enhancements are also identified. The FEA provides a discussion of the important issues and investigates the more relevant available means to address them.

This FEA draws upon achievements and advances in mobile electric power and related technology from the Army, the other Services, other government agencies, academia, and industry. For each technology, an appropriate state-of-the-art is identified, including expectations for the 2015-2025 time frame. Force design principles provide a context for developing a number of criteria to analyze the suitability of each technology. This gives insight into the relative strengths and weaknesses of each technology and enables comparisons in a convenient format. The format is configured as a flexible vehicle for updating the relative importance of each criterion as requirements and technologies develop further.

Background
On 11 June 2001, representatives of the US Army Training and Doctrine Command (TRADOC) and the US Army Materiel Command (AMC) met to discuss future science and technology requirements. An outcome of that meeting was the identification of a requirement to develop a mobile electric power roadmap. The US Army Communications-Electronics Command (CECOM) subsequently identified a need to conduct a FEA of power generation technology prior to commencing the roadmap. TRADOC, CECOM, and the US Army Combined Army Support Command (CASCOM) jointly developed a TRADOC Vision Statement for Mobile Electric Power Research and Development for the 2015-2025 Time Frame, dated 11 September 2001. At that time, TRADOC requested a technology investigation (FEA) and cost benefit analysis for power generation technology for the 21st Century. This FEA follows from that Vision Statement, providing guidance for developing future mobile electric power sources.

The same TRADOC Vision Statement for Mobile Electric Power Research and Development for the 2015-2025 Time Frame appears at the end of Section I of this report.

Scope
This FEA considers various electric power generation technologies, energy storage devices, energy conversion mechanisms, methods of performance enhancement of the various generation and storage technologies, and some relevant information technologies. The power technologies considered are the following: internal combustion engine with electric generator, microturbine with electric generator, fuel cell (with and without reformer), thermophotovoltaics, radioisotope methods, biomass, external combustion, and energy harvesting (wind, solar, etc.)

The energy storage technologies investigated include the following: rechargeable batteries, capacitors, flywheels, superconducting magnetic energy storage, pumped storage, and fuels. A large number of performance enhancements are proposed, but time permitted only a few to be investigated. Nonetheless, this report provides the entire list.

Most significant among the performance enhancements is the impact of information technology. Just as information technologies are revolutionizing the capabilities of the individual soldier, the same advances in technology will revolutionize mobile electric power’s operating capabilities, employment concepts, and maintenance methods.

Mobile electric power is the lifeblood of the digitized modern army. To develop an appropriate mobile electric power source, one must consider what the electric power will do. Important considerations include how warfighting is to be done, what equipment comprises the electrical load, activity level, moving to and about the battlefield, and duration of mission. Power requirements vary with mission, but a single full-spectrum underlying design is necessary to support full-spectrum forces. This report carefully adheres to this concept by first defining the tactical requirements and then investigating how various technologies can meet those requirements.
Vision Statement for Mobile Electric Power Research and Development for the 2015 – 2025 Time Frame

TRADOC envisions a need to have sustained tactical electric power for a minimum of 72 hours without human interface for logistics resupply in the 2015-2025 time frame. Emerging power technologies that show potential for high payoff should be considered for use in the development of the Army’s 21st Century power-generating devices. Additional goals, besides 72 hours of operation without logistics support are further signature, weight, and volume reductions compared to the mobile power system it replaces. Significantly reduced visual, acoustic, and infrared emissions signatures are envisioned to enhance soldier and system survivability. Significantly enhanced reliability and maintainability, together with state-of-the-art embedded sensors and prognostic / diagnostic capabilities, are required.

In both long term and short-term solutions, the key to advanced and alternative power sources is power management. This power management must efficiently tailor power output to load over wide ranges. It must also produce a generating device that provides power only on demand, may increase operation time, decreases the logistics footprint, and reduces total ownership cost.

For the 2kW-10kW range, these potential technologies include kinetic, rotational, wind, direct energy conversion, cogeneration technologies or other forms of motion / chemical reactions used to resupply the given power source during periods when it is not in use. Systems based on these technologies are considered long term, high-risk solutions with potential for very high payoff. Once the feasibility of these technologies is validated and scalability is verified, promising technologies shall be transitioned to address the development of larger power systems (11kW – 200 kW). In the meantime, risk reduction and near term needs will be addressed through the use of advanced materials. These materials will be considered and applied to systems in the 2kW – 200 kW range. They are expected to enhance performance and reduce the size and weight of electromechanical systems.
Section II
Tactical Environment

Introduction
A widespread proliferation of new technologies and advanced capabilities has changed the conduct of war and will continue to do so. Those who best employ these new technologies will have a great advantage in confronting future operational challenges and threats. This is particularly true for the technologies that move energy and information rapidly and effectively.

Advanced warfighting capabilities rely on electric power. It is the lifeblood of the modern digitized battlefield. Information, for use by people and by machines, usually moves by electrical means. As warfighting capabilities advance further, so will demands upon the electrical power that makes them possible. Consequently, there will be important challenges facing tactical mobile electric power in the future years addressed in this report, 2015 – 2025.

This section addresses the context in which these challenges appear. How the Army expects to meet operational and tactical requirements is translated into how mobile electric power will need to perform. First, several broad activities that any ground force must be able to conduct successfully are discussed in the context of how the Army expects to do so in the years 2015 – 2025. Certain important requirements for mobile electric power emerge from this discussion. Second, the changing nature of operational and tactical challenges is analyzed as an electrical load. Recent observations from the Initial Brigade Combat Team (IBCT) and predictions from electronic equipment manufacturers support the analysis. Third, power requirements gleaned from the vision statement are highlighted. Finally, a detailed set of criteria based on force design principles is developed to provide a framework for an analysis of the available technologies in the balance of the report.

Operational and Tactical Challenges
There are several broad activities that any ground combat force must be able to conduct successfully. Tactical electric power must perform in each case without causing a pause or loss of tempo. Tactical electric power must also support rapid transition between activities, again without causing a pause or loss of tempo. The activities are as follows:

- Close combat
- Force protection in close combat
- Tactical maneuver
- Operational maneuver
- Vertical maneuver
- Mobile strike
- Stability and support operations

TRADOC Pamphlet 525-3-0 (1 Nov 2001 Draft) presents the definitions and descriptions of each of these activities for the appropriate future time frame. There is a consistent requirement for unprecedented levels of tempo, lethality, survivability, and endurance. Continuous operations with minimal pauses require innovative sustainment concepts and capabilities, sharp reductions in sustainment demand, significant improvements in reliability, and refined procedures for accelerated throughput, battlefield distribution, and mission staging. Smooth transition from one activity to another becomes an important measure of full spectrum combat capability. Dominant situational awareness is vital, requiring reliable communications, easily digestible information displays, and advanced tactical decision aids. This is heavily dependent upon system of systems advances in C4ISR. The importance of reliable mobile electric power in this environment is obvious.

These activities will also be characterized by discontinuous logistical operations often without secure lines of communication, across greater distances with widely separated units and limited host nation support. There will be significant reliance upon air resupply throughout an operation. Nonetheless, units will engage without the benefit of lengthy theater buildup. Units will have an organic capability to conduct initial operations for significant periods of time, for example, 72 hours, without resupply. A balanced buildup of more forces and more support capability will follow, but units will have a full suite of functional capabilities from the beginning.

The ability to refocus combat support and sustainment rapidly will become key to success. In fact, continuity of sustainment may even be more important than force protection. Maintenance, supply, and transportation support must be packaged to accommodate rapid shifts in sustainment priority, maximize direct throughput to engaged units
and avoid the need to stockpile consumables. It is in this environment that mobile electric power must deliver electric power on demand.

The tactical environment is to be characterized by a quantum improvement in information and command and control connectivity. Investment in technical innovations will seek to maintain the advantage in full spectrum operations. Though emphasis in applying information technology may presently be on command and control systems, there is little doubt that information technology will similarly enhance logistics, promising great advances in effectiveness for supply and maintenance. This will reduce consumption and simplify maintenance and repair. Such advances will exploit the power of information technology and knowledge-building breakthroughs. In operations, forces on all levels will achieve situational understanding and establish, maintain, and distribute a common operational picture tailored to unit and situation. The same will apply to logistics. Information technology will provide the capability for updates in near real time from a variety of automated and human sources. There will be a robustness to preclude interruptions in information flow and situational awareness.

Mobile electric power must be readily able to deploy to the battlefield and provide the platforms that it serves with the electric power that underlies their ability to dominate at any point in the operation. It must enable those platforms to generate maximum combat power when needed. Mobile electric power must do so with minimal logistics footprint and replenishment problems. Taking advantage of improvements in information technology contributes greatly to doing this.

**Changing Nature of the Electrical Load**

Knowing the nature of the load can be helpful in understanding the relative effectiveness of various technologies that may be considered for future mobile electric power production. Certain power generation technologies are better than others to supply certain loads. From the discussion above, it becomes apparent that loads are “power on demand” for warfighters in an environment of unprecedented levels of tempo and sustainment challenges.

This discussion is restricted to the power range specified in the vision statement: 500 Watts to 10 kW. Typical loads in this range may be divided into two categories: electronics and platform. Electronic load includes all equipment that uses electronic components to perform its primary mission. Platform load includes environmental control, fans, lighting, and other loads that do not use electronic components directed to the primary mission. In this power range, loads will ordinarily be mounted on a vehicle of some sort or a trailer. Likewise, any equipment that can generate this level of electric power requires a vehicle for transportation due to its size and weight.

Though predicting what these loads may be with any degree of detail is difficult, the Initial Brigade Combat Team (IBCT) does give some indication. The IBCT Main TOC has a capacity of 173.2 kW from several sources, none of which alone exceeds 10 kW. The typical total load is 81.1 kW, of which 36% is electronic and 49% is cooling. Infantry line battalion TOCs are even more skewed away from electronic load: their capacity is 53 kW, of which they typically use 23.6 kW. 20% of this load in an infantry line battalion TOC is electronic and 68% is cooling.

How is this load expected to change? The International Technology Roadmap for Semiconductors (ITRS) predicts that digital electronics power consumption per advanced microprocessor chip will approximately double by 2014. Processing speeds will increase nearly tenfold, to 13.5 GHz. Other electronic components will exhibit similar power consumption. Because this energy goes to heat, this will increase power consumption both for electronics and for cooling. The mechanics of the cooling hardware will keep this power balance in favor of cooling, though probably slightly less so. The ITRS has updated these forecasts for a number of years and has historically been quite accurate a decade ahead.

**Power Requirements**

The above discussion of the challenges facing mobile electric power, both from an operational and tactical perspective, as well as in an electrical context, lead to a concise listing of requirements that are summarized below. First, operational and tactical requirements for the proposed time period, years 2015-2025, reveal the following for this range of mobile electric power:

a. A single underlying basic design is preferable. The full spectrum forces that this equipment supports may have certain special purpose capabilities, but they should still be full spectrum forces. Doctrine
discourages unique designs for specialized forces. Commonality simplifies and reduces sustainment, supports multifunctionality, and reduces the numbers of supporting skills.

b. Effectively provide the electric power demanded immediately upon arrival. Once in operation, continue to provide electric power on demand without causing a pause or loss of tempo even as operations rapidly shift from one activity to another.

c. Easily assigned to loads with a minimum of interface complexity, but having flexibility to drive as wide a range of loads as possible.

d. Anticipates the impact of new technologies and be able to incorporate future advances in technology quickly into the design when appropriate.

e. Avoids overdesign by modularizing any special capabilities. This reduces the temptation to “bring everything”, thereby reducing deployment payload.

f. Provides excellent fuel efficiency from highly reliable and maintainable equipment. The high tempo infers that this equipment will be heavily reliant on air resupply, making a small logistics footprint desirable.

g. Fits into a knowledge-based C4ISR system architecture. This is important as information technology becomes increasingly applied to this equipment’s design.

h. Easy for the soldier to install, operate, and maintain.

i. Affordable acquisition and life cycle costs.

From the vision statement presented at the beginning of this report, some other power requirements are readily gleaned and help define the scope of this investigation:

a. A power range from 500 Watts to 10kW.

b. Sustainment for 72 hours without human interface.

c. Improved reliability and maintainability; “Electrical power on demand”

d. Mobile with weight and volume reductions vice current technology. This influences deployability.

e. Signature reduction: visual, acoustic, and infrared

f. State-of-the-art sensors and prognostic / diagnostic capabilities

g. Scalable to greater electric power ratings.

Force design principles
The six force design principles in TRADOC Pamphlet 525-3-0 (1 Nov 2001 Draft) are as follows: deployability, agility, versatility, lethality, survivability, and sustainability. In employing these principles, the desired result is an Army force that is strategically responsive and dominant at every point on the spectrum of military operations. For mobile electric power, a number of indicators show how well these design principles are being observed.

Deployability is defined as ease of movement to the battlefield of mobile electric power systems based on a particular technology. Movement of the systems will be by C-130 type aircraft and all items must meet the requirements for aircraft configuration. Indicators include:

- **Weight:** total mission weight, including machinery, power conversion systems, fuel, tools, maintenance equipment, and appropriate spare parts for 72 hour operation.

- **Size or Volume:** total cube, including all items mentioned above

- **Energy Density:** amount of energy per unit weight that a mobile electric power system can provide. A term most often applied to batteries.

- **Specific Energy:** amount of energy per unit volume that a mobile electric power system can provide. A term most often applied to batteries.

- **Power Density:** amount of power available per unit weight. Power is the time rate of energy flow.

- **Specific Power:** amount of power available per unit volume.

Versatility is defined as how consistently well a mobile electric power system based on a particular technology enables the capacity of the platforms that it supports to dominate at any point in the operation. Indicators include:

- **Scalability:** Mobile electric power equipment should perform consistently well as rated, whether designed for 500 Watts or for 10 kW or any power rating between. The vision statement also requests an estimate of how well mobile electric power systems based on the same technology perform when built for ratings up to 200 kW.
**Environmental Compatibility:** Mobile electric power equipment encounters wide ranges of temperature, humidity, atmospheric composition, dust, attitude, etc.

**Reliability:** Power on demand. Perfectly reliable systems perform as specified whenever requested to do so. Simplicity and ruggedness are ingredients of reliability. Mobile electric power systems must exhibit high reliability because lives may be in jeopardy if they fail.

**Mobility:** Once deployed, a mobile electric power system should be at least as easy to move around the battlefield as the equipment that it supports.

**Availability:** Whether a mobile electric power system may be present and ready for use whenever needed. Solar cells are an example of a mobile electric power technology that has less than perfect availability. Redundancy is a common method of enhancing a mobile electric power system’s availability; so is energy storage.

**Ease and speed of start and restart:** Starting and restarting a mobile electric power system should be easy and quick. This indicator also includes effect of numerous start-stop cycles.

**Energy storage requirements:** Energy storage is a common method to improve availability and speed of start. It also helps a mobile electric power system ride through disturbances.

**Step response:** An indicator of power on demand. How the mobile electric power system performs when presented with a demand to increase or decrease power output as rapidly as possible. This includes speed of response and the path taken.

**Length of service:** What resources are necessary to gain acceptable performance for a given time, for example, 72 hours? Included is whether more or less than a proportional share of resources are required for shorter missions.

**Peak factor:** The ratio of peak load to average load. Some loads exhibit a pulsed behavior or vary significantly with time. If mobile electric power units based on a particular technology are less capable of handling such a load, then the unit chosen must have a higher average power rating than a more capable unit based on another technology. Units with higher average power ratings generally consume more resources.

**Duty cycle:** Do units based on a particular technology have an advantage on missions with predictable on-off operating conditions for some or all loads? Such situations benefit greatly from dynamic power management.

**Survivability** refers to how well a mobile electric power system based on a particular technology mitigates the effects of combat and affords safety and protection for the soldier.

**System survivability:** Equipment in general should have a reasonable capacity to survive the effects of combat. These include nuclear, chemical, and biological effects, results of electronic warfare, as well as traditional hazards of battle such as blast, fragmentation, bullets, etc.

**Safety:** A mobile electric power system must be safe for the soldier to operate. It must not subject the soldier to high temperatures, noise hazards toxic exhausts, dangerous chemicals or fuels, electric shock, fragmentation, explosion, or any other safety hazard.

**Infrared signature:** All mobile electric power technologies produce waste heat. Some portion of waste heat energy is emitted as infrared radiation. This signature is difficult to defeat.

**EMI signature:** Electromagnetic interference. This can interfere with communications. An enemy can also detect it.

**Audible signature:** The effects of audible noise can be assigned to three categories: a health hazard, interference with communications, and noise that renders the soldier detectable by the enemy. The first two categories are addressed in human factors engineering references. Though difficult to assess, detectability is a significant hazard.

**Visible Signature:** Detection by visual means is a problem, though camouflage can mitigate it somewhat. Some systems have reflective surfaces or distinctive packaging that render them vulnerable to visual detection.

**Human factors:** This refers to how well a particular technology lends itself to designs that the soldiers finds easy to use and maintain. MIL-STD-1742 and MIL-H-46855 provide comprehensive requirements for human factors.

**Sustainability** refers to the logistics footprint of a mobile electric power system based on a particular technology and the amount of resources necessary for replenishment.
Cost: Cost is difficult to define, yet one of the more important factors. Acquisition cost refers to how much, by comparison, it costs to bring the technology to a form that the soldier can use. Life cycle costs include research, development, procurement, sustainment, and disposal costs of a particular technology. Costs of continuing to support legacy equipment must be included.

Shelf life: Ability to store units in a non-operating mode when not required. This may require special equipment or facilities.

Maintainability: Soldiers should not have to invest unreasonable amounts of time and effort to keep a mobile electric power system in operation. Replace forward (modular construction and plug in / plug out parts). Repair rear. Embedded prognostics and diagnostics required. Simplicity of design and operation. Requirements for such maintenance items as spare parts, lubricants, and tools should be minimized by design.

Production base: A technology with a large production base has desirable properties of cost, competition, availability, and insensitivity to variable demand. Technologies that require rare materials or have unusual or difficult manufacturing processes are less desirable.

Possibility of REMEDYING inherent deficiencies within 20 years: Important in this study. There should be advances in nearly all of the technologies under consideration. Though some may be impractical now, they may become practical within twenty years, the time period for this study.

Environmental impact: Soldiers and the citizens that they serve will continue to live on the planet. Using environmentally friendly technologies whenever possible enhances that quality of life.

Political impact: Certain technologies are more acceptable politically than others. For example, nuclear batteries usually draw a strong adverse political response, as the Cassini probe recently demonstrated. Solar cells are seen as a good thing by most of the population.

Conclusion
In the 2015 – 2025 time frame, war will be fought and won differently than it is today. The Army will remain optimized for major theater war, but will become versatile and agile enough to handle smaller scale contingencies well. In other words, forces must be decisive at every point on the spectrum of military operations. Units will enter the conflict with a minimum of staging and must be immediately capable of conducting simultaneous, distributed and decisive combat operations. They must move smoothly from one category of mission to another and back again w/o loss of momentum or operational focus. This will require a revolution in military logistics, incorporating advanced capabilities and new logistical concepts. Units must enter with enough inherent self-sufficiency to conduct initial tactical operations without augmentation.

This environment presents big challenges for tactical mobile electrical power. It must produce power on demand for a range of loads from a single underlying basic design. A host of important considerations must be met, from safety and ease of use to affordable costs at every stage of its life cycle. To help analyze the relative ability of various technologies to meet these challenges, a number of indicators have been grouped by force design principle. In the next section of this report, the various technologies are introduced and analyzed to determine which is most likely to be the best to provide future tactical mobile electric power.
Section III
Power Technologies

Introduction
For the 500 Watts to 10 kW power range, several technologies provide a basis for generating mobile electric power. In each case, the fundamental physics has been known for quite awhile. However, each technology advanced significantly in recent years. Some of these advances may be described as improvements in the basic technology itself. This report identifies such significant advances and discusses those that apply to tactical mobile electric power. In addition, many of the recent advances intelligently use information for advanced control techniques and insightful methods of performance enhancement. This trend shows no sign of slackening. On the contrary, the research literature across the board reveals a growing propensity to address performance issues with technology based on the intelligent and rapid application of information.

In this report, the following potential technologies are considered:

- Internal combustion engine with an attached electric machine
- Turbine engine with an attached electric machine
- Fuel cell, with or without a fuel reformer, with an attached power electronic converter
- Thermophotovoltaic generator with an attached power electronic converter
- Radioisotope (thermal or particle based) generator with a power electronic converter.
- Biomass to provide fuel for other technologies
- External combustion engine with an attached electric machine
- Energy harvesting, including wind, photovoltaic, biomass, human, hydroelectric, wave and tidal, and geothermal.

In general, systems based on these technologies have a long term future in electric power generation. Each has advantages that make it competitive for a certain set of applications. This report investigates which of these technologies might be best suited for it.

Internal Combustion Engine
The Tactical Quiet Generator (TQG) embodies the current state of technology in tactical mobile electric power for the Army. Its prime mover is a diesel engine, operating at a single speed. Its electric machine is a wound-field synchronous generator directly connected to its load. The next generation will be the Advanced Medium-sized Mobile Power Sources (AMMPS), also driven by a diesel engine. Its electric machine is a permanent magnet generator that supplies its load through a power electronic converter. AMMPS equipment operates at variable speed, variable frequency, and variable voltage. Its power electronic converter creates the fixed frequency, fixed voltage amplitude that its loads require.

Though improvements in other energy technologies get much of the publicity, the technology of the internal combustion engine technology is by no means standing still. Internal combustion engines can expect to benefit from a number of technology enhancements, including advanced materials, improved fuels, and advanced control technology based on intelligent use of information. In fact, a publication as prestigious as the Proceedings of the IEEE acknowledges in December 2001 that the stream of technological innovations expected in internal combustion engines poses a substantial problem for competing technologies. The article goes on to state that the advent of the Hybrid Electric Vehicle (HEV) will even accelerate these advances. The literature shows the internal combustion engine dominant in the near term for all the purposes for which it is presently used. It also appears to be quite competitive in the far term. Department of Energy (DoE) projections reveal similar analysis and conclusions.

For reasons discussed in a later subsection of this report pertaining to fuels, gasoline engines are considered a less desirable internal combustion engine for tactical mobile electric power. Compression engines have the reputation of running for longer periods of time, handling greater loads, and requiring less maintenance for a given physical size. In fact, Ford repeatedly states that a diesel engine remains a strong competitor for inclusion in all its HEV products. Therefore, internal combustion engines that use tactical fuels will be considered in this report.
Improvements in materials:

Improved materials will appear for the following purposes: increased use of composites for strength, lighter weight, and better heat and acoustic insulation; ceramics for better wear; improved metals for heat transfer,… The net effect is projected as approximately a 20% improvement in fuel economy by 2015.

*Increased use of composites:* Composite materials provide the common advantages of lighter, tougher frames, housing, skids, and mounts that apply to the internal combustion system. Advantages in acoustic insulation will improve the acoustic signature by a few dB. Unfortunately, this improvement will be fairly limited because internal combustion engines tend to have a lower frequency range that is more difficult to damp than the higher frequencies that are generally characteristic of other technologies. Internal combustion engines already emit the greatest acoustical noise of any of the available technologies and will continue to do so, a few dB of evolutionary improvement notwithstanding.

In an internal combustion system, cylinder blocks and catalytic converters will exhibit increased use of composites to reduce weight and to reduce mass moment of inertia. Combined appropriately in the matrix with metals, composite materials will retain heat more efficiently where it is needed for greater performance and channel heat away from where it is undesirable. There will be significant evolutionary improvement in this.

*Ceramic coatings and parts:* Though operation without lubricants is unlikely within twenty years, ceramic parts and coatings will greatly reduce the need for lubricants. This may lead to a resurrection of two-cycle compression engines for some purposes, but they will likely remain impractical for even the smaller mobile electric power units. Ceramic coatings in the cylinders impede heat transfer, increasing engine combustion temperatures and reducing heat loss. This improves exhaust properties, contributing to more effective energy scavenging.

Improvement in fuels

The relatively safe, efficient transfer of energy in the form of petroleum-based fuel contributes a great deal to the internal combustion engine’s present dominance in transportation and in mobile electric power. There is little indication that this dominance or its underlying reason will change in commercial applications within the next twenty years. Consequently, industry has been able to afford to focus on improved emissions from petroleum-based fuels, an important goal that may be more significant for commercial applications than for military ones.

For internal combustion engines, information-based improvements discussed below may lead to selectively increased use of renewable fuels, such as alcohols. However, these will most likely be blended with petroleum-based fuels. Sole use of renewables or hydrogen would require a great change in the world’s fuel distribution infrastructure. It is well known that creating a distribution infrastructure for any product costs far more than bringing the product production. Therefore, if the commercial technology of choice for transportation remains the internal combustion engine (and that is indeed most likely), then the availability of petroleum-based fuels and the expense of reconfiguring the fuel distribution system makes such a change to renewables or to hydrogen unlikely in the next twenty years.

Information-based control technologies

Many of the more exciting developments in internal combustion technology in the next twenty years may be described as advances in information-based control technology. Some of these advances are already beginning to appear in the marketplace. Others are still in the laboratory. Though accurate prediction is difficult, it is likely that several, if not most, of them will be commonplace by 2025. Several of these technologies offer advantages at light load conditions, an unfortunately commonplace situation for many tactical mobile electric power systems.

*Variable valve lift and timing:* With the advent of better actuators and more precise control of them, valve lift and timing can be tuned for different speeds. This enables injection at stoichiometric ratios for a more complete fuel burn over a range of speeds and loads. Prototypes of engines with this capability already exist.

*Programmed cylinder deactivation:* This is an old idea with an information technology upgrade. For lighter loads, individual cylinders can be omitted from the firing sequence. Instead of deactivating the same cylinders each time, prescribing a computerized pattern tunes the vibration and aids in cooling. Mercedes has this on some of its 2002 models. It will also appear on early HEV models.

*Variable response forced injection:* The benefits of turbocharging are well known. Information-based control technologies can vary the inlet vanes in a prescribed fashion, improving efficiency over a wider range. This technology is still in the academic laboratory.

*Variable compression ratio:* Typically, the expansion ratio equals the compression ratio. However, fast control technology can improve on this, increasing the expansion ratio by holding the valve open longer as a
function of speed and load. This gives better performance, particularly under light load. Electromagnetic valve actuators, though mostly still in the laboratory, contribute to this flexible performance.

*Homogeneous Charge Compression Ignition:* an experimental technology that has similarities to pulse width modulation. For example, the cylinder can be charged with several pulses of fuel of appropriate duration. In doing so, fuel gets distributed throughout the cylinder in a more advantageous fashion. Burn is more complete at a leaner ratio and a lower temperature. Fuels with higher proportions of alcohol and even water can be used. This technology is known to work at light loads, but has stability problems at heavier loads.

*Multistage direct injection:* Directly inject the fuel into the combustion chamber, atomizing the fuel during injection. When teamed with multiple pulses of fuel, more complete combustion at lower temperatures for a range of fuels is possible. Information-based control technologies permit adaptation to a range of conditions.

*Improved real time diagnostics and control:* Digital control can be applied to a range of important variables, including pressure, speed, temperature, coolant and lubricant variables, and timing. Each can be corrected in real time in closed loop control algorithms. Sensors abound and will proliferate much more in commercial engines in the future. Their hunger for electric power is one driving force behind the move to 42 Volt automotive electrical systems.

*Spark ignition of tactical fuels:* Several of the advances mentioned above can blur the distinction between Diesel and Otto cycles. Prototypes of such systems exist in academia, though it is unclear how competitive they will become in twenty years for anything but the smaller generators.

The Hybrid Electric Vehicle (HEV) has attractive possibilities for the internal combustion engine beyond those mentioned above. Though other technologies may eventually supplant the internal combustion engine for HEVs, initial models will have it. Ford continues to consider a diesel engine for its entire HEV product line for the foreseeable future. If the internal combustion engine proves to be the HEV technology of choice for the next decade or so, then it may be possible to consolidate the transportation and tactical mobile electric power functions of many systems that the Army owns. In other words, equipment mounted on an HEV could be electrically powered from the HEV’s power plant itself, eliminating the need for a trailer-mounted generator. This does aggravate the problem of light loads, however. Power levels specified for the automotive engine in a military HEV are expected to be at least 50kW. That is somewhat greater than most of the expected electrical loads that it would carry. Power management and information-based control techniques may be able to mitigate this problem, possibly through greater reliance on the electrical portion of the HEV. These are discussed further in a later section of this report.

A number of the information-based enhancements are already starting to appear in HEV designs. For example, Toyota advertises its HEV as actually turning off the engine when not needed. The engine then rapidly restarts using an electric assist algorithm. Toyota includes a computerized random cylinder deactivation algorithm, particularly effective under light load, to reduce vibration and enhance cooling. Because the algorithm is digital, it is possible to program it to mimic a wide spectrum of acoustic and thermal signatures.

**Effect on the Electrical side of the system**
Because the internal combustion engine provides output energy in a kinetic form, conversion of that energy to an electrical form requires an electric machine. The optimum speed of the engine varies with load. In the electric machine, speed, frequency, and voltage are closely related. Power electronics can convert the electric machine’s variable frequency, variable voltage output to the fixed frequency, fixed voltage that the load requires. The technology for doing all this has been well known in the Uninterruptible Power Supply (UPS) industry and in the wind turbine generator industry since the mid-1980s. The fuel cell industry also possesses the appropriate technology. In recognition of this fact, Ford (automobiles) teamed with Ballard (fuel cells) in 2002 to produce small electric generators driven by internal combustion engines, not fuel cells. This diversification speaks volumes about Ballard’s view of the future of automotive power technology.

The lower speed of the internal combustion engine, when compared to other rotating systems, requires greater weight and volume for its electric machine partner. Lower speed also leads to lower generator voltages and greater voltage ripple, a challenge overcome at some cost by the power electronics. The limiting factor is the thermal capacity of the power electronic devices and is likely to remain so. These issues and other electric machine issues are common to other rotating systems and are discussed in the power electronics and electric machines sections of this report.
Conclusions:
The internal combustion engine will probably remain the leading alternative to drive a tactical mobile electric power system. This will be due to its head start at the present leader and to expected advances in materials, fuels, and control technology that is based on intelligent use of information. Though other technologies may get the publicity, the internal combustion engine will continue to show great performance advantages.

Turbine Engine
Though turbine engines have been available for many years, a turbine engine as a competitive means of mobile electric power generation is a relatively recent development. In the past couple decades, the “microturbine” has advanced to become a realistic technology for an electric power source. Its ancestry rests primarily in technology from the aircraft and turbocharger industries. By the early 1990s, a few companies, primarily from the Western US and Japan, began to make it into a prime mover for a modular emergency electric power source. These successful efforts widened into a range of practical electric generators that have a degree of portability.

Advances in information-based control technology have been the basis of its success. Adaptations of that technology have led to a self-contained, portable system. For example, high speed control technology closely regulates combustion in such a small turbine. Advanced signal processing applied to electrical networking enables any number of these turbines to be connected and regulated separately. The primary niche for microturbine technology so far has been in the power quality industry and in distributed generation, both particularly popular markets in the Western US.

Advantages of a turbine
As a prime mover for an electric power generator, a turbine has some significant advantages. These are due to certain favorable behaviors in the underlying physics and are also due to the microturbine’s coming of age in an environment rich in information-based advances in technology. Its most significant advantages include the following:

Mechanical simplicity: At its heart, a microturbine has only one moving solid part, its rotor. There are no other high speed parts to balance, lubricate, or wear out. In fact, the low speed auxiliary “computer” fan that cools its embedded electronics is by far the most common failure mechanism.

High energy density: High rotating speed gives both the turbine and the electric machine the advantage of smaller size, lighter weight, and greater energy density for a given power output capability. In a typical 30kW unit, the turbine and electric generator combine to occupy less volume than a soccer ball.

Length of service: A microturbine with sufficient fuel can easily be expected to run for 72 hours (and a lot longer) without further human intervention.

Fuel: A turbine engine runs on a variety of fuels. It comes closer to having a universal fuel capacity than any known technology. In fact, any combustible fuel that can be injected into the air stream can burn. Any sustainable burn provides continuous power. It requires only a simple, easily prepackaged hardware modification to change from running on liquid fuels, such as gasoline or diesel fuel, to using gaseous fuels, such as natural gas or hydrogen. Changing from one liquid fuel to another is a matter of adjusting the air-fuel mixture proportions, a task easily installed in the software.

Acoustic noise: Without shielding, a 30 kW Capstone microturbine has a peak acoustic noise level of 65dB at ten meters. This is similar to the Tactical Quiet Generator with shielding. Because its acoustic noise is at a somewhat higher frequency (16 kHz) than the acoustic noise from an internal combustion generator, the turbine is easier to shield acoustically. For example, a dozen commercial units together behind an ordinary glass window emits less than 45 dB at five meters. A Japanese 2kW unit already tested at CECOM emits 53 dB at 11 kHz at seven meters.

Emissions: In one of its internal microprocessors, a turbine can calculate its air-fuel mixture to achieve optimum proportions and then command the hardware to properly adjust continuously. As such, turbines generally burn fuel more completely and have a lower level of undesirable emissions than internal combustion engines. Unfortunately, that level of undesirable emissions is still greater than what hydrogen fuel cells produce.

Long life: Turbine-based generators typically have a rated life of at least 40,000 hours. This is more than six times the rated life of the Tactical Quiet Generator. It is more than twenty times the optimistic estimates for PEM fuel cells burning hydrogen. Start and stop cycles have no significant contribution to shortening the life of a turbine. The performance of turbines as prime movers in commercial buses supports a perception of ruggedness.
Air bearings and air cooling: The high rotating speed provides the opportunity for air bearings, favorably affecting lubricant requirements and spare parts load. Air cooling reduces the load that must be deployed to support the generator in the field.

Electrical interconnect: Reliable software already exists to electrically interconnect and synchronize 100 microturbine generators through an RS232 communications interface. This brings to the tactical level the improved reliability of networked electrical generators.

Disadvantages of a turbine
The turbine-based generator has some significant disadvantages:

High manufacturing costs: A turbine is somewhat more expensive to design and build than an internal combustion engine. Speeds are high, so tolerances are exacting.

Speed change: The turbine changes speed on command somewhat less rapidly than an internal combustion machine. This can be a problem, particularly when the machine is lightly loaded. At light loads, the turbine in intentionally slowed to help maintain efficiency. Any quick increase in load cannot be met without energy storage. To provide a greater bandwidth for load changes, many turbine generator sets include a battery. The battery is often greater in size than the turbine and generator combined, unless the customer is willing to tolerate brief sags or swells when loads change. If the customer is willing to tolerate lower efficiencies, then better transient response is possible. Even so, the turbine’s ability to meet rapid changes in load is far superior to a fuel cell’s ability to do so.

Complexity vs. efficiency: To achieve an efficiency that is greater than most gasoline engines, the turbine must recapture energy in the exhaust stream. Hence, intercoolers, regulators, and reheaters appear in the system. This adds complexity, weight, and volume.

Volume: The turbine and generator are indeed quite small for the energy that they process. Unfortunately, the battery, energy capture equipment, and power electronics nearly triple the size of a typical turbine system. As a result, the volume is comparable to that of a Tactical Quiet Generator for the same power rating.

Production base: This is a relative new application for a known technology. The production base is still quite small. It does rely on technologies that are well known in the aircraft and automotive industries, so rapidly increasing production may be possible.

Performance issues
Efficiencies are typically 25%-30% at rated load. However, at light load (below 30% of rated load) without speed reduction, efficiency is significantly less. Therefore, light load is addressed through a combination of speed reduction and control of fuel consumption. Power electronics compensate for a reduced voltage and frequency that occurs with lower speed operation. (This concept is quite similar to the way AMMPS preserves efficiency at lighter loads.) Reducing fuel flow reduces torque and current with adverse effect on system operation.  As such, the system can run lightly loaded for long periods of time without other adverse effects.

Startup is typically about 90 seconds, more than that required for an internal combustion engine, but less than a typical fuel cell. However, startup is usually fully automatic, being controlled by the on-board microprocessor. Many microturbines already have the software to be started remotely while providing several status indicators through an appropriate data interface.

Electrical topology is quite similar to that of an on-line Uninterruptible Power Supply (UPS). There is an active rectifier on the generator side and battery storage on the dc link. The electric machine is based on a permanent magnet machine design. Because speeds are somewhat higher than those found in internal combustion systems, the generator is somewhat smaller and has a greater power density.

A number of microturbine generators are already in operation, most of them providing cogeneration and backup power for light industry. Units are commercially available from about 2.5kW up to 60kW. In the military realm, the Marine Corps began testing of a tactical microturbine-based 30 kW generator at Twenty-nine Palms in February 2002. Boeing plans to demonstrate an microturbine-based HEV concept in a combat vehicle in 2002. They propose production in 2007. Therefore, it is likely that the microturbine will be a common and reliable technology before the year 2015.
Research trends
Research continues to address several issues. However, some of the important issues are not being addressed by the microturbine manufacturers directly.

Scaling. Scaling up and down appears to be quite possible. At present, the research emphasis is on scaling up. Theoretical limits for scalability upward are yet unknown.

Ruggedness. Ruggedness is an important issue for military applications. Several city buses with microturbine-based HEV topologies have been running for over two years without a single failure. The results of the Marines’ testing, mentioned above, will be enlightening. The same company has offered to send the same unit to CECOM for tests during the summer of 2002, after the Marines are finished with it.

Performance with heavier fuels. For machines with low power ratings, heavier fuels have difficulty maintaining combustion. That problem does not occur in the power range under consideration for this investigation.

Air filter. Microturbines are sensitive to particles in the airstream. Existing filter technology keeps this from being a significant failure mechanism. Cleaning the air filter is the most frequent maintenance requirement. This is actually not a big problem: the number of hours between recommended filter cleanings is slightly greater than the entire rated life of a TQG.

Power electronics. Most microturbine manufacturers now buy these off-the-shelf from power supply manufacturers. They have found it too expensive to design these in-house. The trend to modularity, driven by cost, in most commercial power supplies has encouraged this.

Battery. Response to rapid changes in load depends on energy storage. In this case, this means batteries. The battery is the largest item in a microturbine that is designed to support applications that would be considered to be C4ISR in nature.

Information Technologies: Because microturbine generator technology came of age recently in California and Japan, it has taken advantage of computerized diagnostics from the beginning. All microturbines contain a number of operator-level diagnostics and datalogging, typically with a simple on-board alphanumeric display. All microturbines also have a host of diagnostics and additional datalogging for organizational and support maintenance. These are usually interfaced through a data connection, e.g., RS232, to a computer with supporting software. Wireless communication for the entire suite of diagnostics and datalogging is in beta testing.

Conclusions
It is difficult to predict where microturbine technology will be by 2015. Even its manufacturers do not publicly make such predictions, unlike proponents of most other technologies. However, the microturbine appears to be one technology that can give the internal combustion engine some serious competition for tactical mobile electric power applications. The microturbine is quieter and more reliable than an internal combustion engine, can operate for 72 hours without attention, has a nearly universal fuel capability, and has already incorporated a great deal of information technology into operation and maintenance.

Fuel cells
Fuel cells offer efficient, clean, quiet electrical power. Fuel cell manufacturers routinely claim efficiencies greater than 30% and many claims are above 50%. In cogeneration situations, efficiency claims can be substantially higher still. The fundamental fuel cell reactions produce no harmful emissions, hence the reputation for clean operation. Even the reformer reactions normally produce fewer harmful emissions than comparably rated internal combustion engines, turbines, or other generation technologies. Fuel cells produce a clean direct current, free from harmonics and most other power quality problems. Proton Exchange Membrane (PEM) fuel cells have become packaged for easy handling, lacking the corrosive constituents and high temperatures of their larger cousins. A Solid Oxide fuel cell, the other candidate fuel cell for military use in the medium power range, shows similar advantages, except for its somewhat higher operating temperature. Ordinarily, the only acoustic noise produced by a PEM fuel cell is from an occasional small fan or pump in a supporting subsystem. To obtain ac output from a fuel cell, only a single dc to ac conversion is required. This requires about half of power electronics as variable speed generation using rotating machinery, for example, AMMPS.

There is little doubt that fuel cells can be produced in the desired power range (500W – 10kW). Hydrogen fuel cell stacks already exist. Ballard and others sell reliable PEM fuel cell stacks as OEM items in this power range, though they lack a large market yet. The problem with this avenue is not the existence of technology or the ability to
manufacture the hardware. For example, if given the orders, a president of a Teledyne Energy Systems guaranteed that he could use today’s technology to produce 100,000 units annually of a commercial 10 kW PEM hydrogen fuel cell in about three years. Web process industries already have the technology and the manufacturing capability to make the membranes. He guaranteed similar numbers of a reformed methanol PEM fuel cell within five years. This man has credibility, having gained a reputation (and a presidency in a Fortune 500 company) for taking a number of products with a solid underlying technology from prototype to full production. Others who also manufacture fuel cell have similar forecasts.

Three avenues to obtaining a feasible fuel cell technology
Of all the available technologies, the performance claims for the fuel cell are the most difficult to unravel. There is a great deal of hype from a wide range of sources. Fuel cells have an unfortunately long history of being just a few years away from success, a situation that does not help anyone winnow the truth. However, there are some indicators that reveal something about the state of the technology and where it may be going. There appear to be three overlapping avenues to a practical fuel cell for military applications: build an appropriate fuel distribution system, develop appropriate reformer technology, or create a reformerless technology, such direct methanol. The resources required to perform any one of these three alternatives exceed what one might consider reasonable for tactical mobile electric power to commit alone. The necessary resource requirements are probably too great even for tactical vehicles, a somewhat larger market for which fuel cells have been proposed. Therefore, building on the commercial infrastructure is necessary to make the fuel cell feasible for powering tactical systems.

Hydrogen is the fundamental fuel of the fuel cell. The problem with using hydrogen as a fuel is fuel distribution and storage, hence the first avenue to success listed above: build an appropriate fuel distribution system. Developing a storage and distribution infrastructure for hydrogen is a great expense, without doubt requiring far greater resources than those required to bring the fuel cell itself to commercial viability. There are also technological problems to overcome in creating such a system. For example, storage requires either high-pressure containers or the use of other materials, for example, metal hydrides. Significant improvements in cost, energy density, safety, and public acceptance are necessary before such methods can be practical. In fact, an unfavorable safety perception, for commercial or battlefield storage, is a formidable obstacle to introducing hydrogen as a fuel. Therefore, using hydrogen directly as a commercial fuel will be impractical for the foreseeable future.

A second avenue is to develop appropriate reformer technology. Hydrogen remains the fundamental fuel, but it may be produced on site, or reformed, from other fuels. Reformers for common fuels are at various stages of development, from beta prototypes of methanol reformers to some rudimentary work on diesel reformers. As mentioned above, there is little doubt in industry or government that methanol reforming will be a well-developed technology by 2015. In June 2002, General Motors claimed discovery of the first reformer for low-sulfur gasoline. Its fuel cell powered a pickup truck to nearly 40 miles per hour. It will be more difficult to obtain reformers for diesel fuel, kerosene, or JP-8. No viable reforming technology for those fuels exists yet. It is not clear whether such technology will exist by 2015, but the outlook is not good. The military is the only major customer who wants the technology. Provided a successful reformer can be developed, European industry prefers methanol as a fuel and US industry favors gasoline. Consequently, the huge research investment necessary to develop a reformer for tactical fuels is not being committed. That is unlikely to change soon.

PEM fuel cells are quite sensitive to carbon monoxide and even more sensitive to sulfur. Carbon monoxide is a byproduct of some of the steps in certain reforming processes. Host nations that are less developed may have only fuels with high sulfur content. Reformers require extra components to eliminate carbon monoxide and sulfur. This adds greatly to deployment weight and volume. It also explains why some people prefer hydrogen as a fuel despite the expense of building a distribution and storage network. (As an aside, the extreme sensitivity to sulfur even raises questions of the PEM fuel cell’s vulnerability to chemical warfare with sulfur-based compounds.)

A third avenue is to develop a fuel cell that does not require a reformer. Direct methanol fuel cells are an example of this. There is an advantage in size and perhaps complexity. However, direct methanol fuel cells have a reputation for an even shorter life than even their short-lived brethren. Direct methanol fuel cells also require a more advanced catalyst technology. Though direct methanol fuel cells may be a possibility within twenty years, having similar systems for other fuels by then is not likely. As with reformer technology, a huge research investment is not being committed to direct fuel cells for tactical fuels because a market is unlikely anytime soon.

Front End Analysis
Mobile Electric Power Research and Development for the 2015-2025 Time Frame
Other fuel cell performance issues
Other common fuel cell problems may be grouped into several categories: water management, responsiveness, materials and components, and cost.

**Water management:** Water is produced by the reaction at the cathode. The membrane must be hydrated. Water migration influences performance greatly. Water management is a complex problem, but it has generally been solved. Some startup problems remain and some questions about the how water management influences length of life still are not completely solved, particularly when cold temperatures are a factor.

**Responsiveness:** Fuel cells require a few minutes to start up, though this problem is less pronounced with low temperature fuel cells such as PEM fuel cells. The bandwidth for response to changes in load is less than that of internal combustion engines and turbines. This means that a great deal of energy storage may be necessary to avoid power quality problems.

**Ruggedness:** The ruggedness of the fuel cell on a mobile platform is still largely unknown. There is insufficient data on fuel cell performance and life as part of a mobile system. Performance of a PEM fuel cell at low temperatures becomes a problem due to water management. It is largely unknown how well membranes stand up to vibrations that an Army generator often faces. Frequent startup and shutdown may be more life limiting than long periods of continuous operation.

**Materials and components:** For a fuel cell system, the combination of materials necessary for performance can be quite complicated. Appropriate materials for the stack of a hydrogen fuel cell are well known. Reformers add a degree of complexity that influences size, cost, reliability, and life. A practical reformer does not exist for tactical fuels. Even for direct methanol fuel cells, there is a tradeoff between better materials and length of life. Better catalysts will be found, but it is not clear how soon. For example, Solid Oxide fuel cells really need better cathode materials. Occasionally, a fuel cell chemistry having some rare components appears, a situation that should be a reminder that the industrial base must support any product that soldiers use. Overall, a fuel cell is a complicated system requiring many diverse materials. Most of these materials and components problems have been solved for hydrogen fuels, but somewhat fewer have reached solution for other fuels.

**Sensors and control technology:** The fuel cell requires more sophisticated control methods than most other power technologies. Quite a few sensors must report on a large number of conditions within the fuel cell. Appropriate control methods are necessary to maintain stability and reasonable performance. These sensors and control methods currently exist and will improve significantly in the future. Developments in other technologies, turbines for example, can be leveraged. However, these sensor requirements add to cost, weight, and volume and generally detract from reliability.

**Cost:** The fuel cell is somewhat more expensive than its major competitors for a similar power rating. It requires expensive materials in some components and is quite complicated. Economies of scale will appear only if the fuel cell develops a significant market. Hidden in the cost figures is the rated life of the product. Today’s fuel cell stacks have a rated life less than one quarter of that of a typical diesel engine of a comparable power rating and less than 6% of that of a comparable microturbine. Though these numbers will improve, it is unlikely that fuel cell system life will exceed that of its major competitors by 2015. For this reason, it is difficult to obtain an estimate of life cycle cost for a fuel cell; estimates vary widely but all appear unfavorable.

Research trends
There is no consensus among those in the fuel cell industry as to which reformed fuel would be best. Europeans appear to favor methanol, reformed or not. Beta prototypes thereof exist already. Americans seem to have a preference for natural gas or gasoline reformers, though that technology lags methanol reformers. Nonetheless, methanol reformers already exist. Natural gas and gasoline reformers are likely in twenty years. The military and the trucking industry have an interest in diesel reformers, though none appears likely in the foreseeable future. Consensus in the fuel cell industry is that hydrogen storage and distribution technology should be a strong focus of research. There seems to be more confidence that a hydrogen distribution network will be easier to build than a practical reformer for fuels already having a strong distribution network. Because a distribution system must be built to make hydrogen widely available, large investments are necessary. For that to happen, the fuel cell will have to exhibit somewhat more promise than appears likely today. Technical, economic, and policy bases for choosing a fuel (either hydrogen or a reformed hydrocarbon fuel) are not likely to be available until fuel cell processor technology development efforts have proceeded further and the infrastructure and environmental implications of different fuel choices are better understood, probably by 2006 or so.
Microchannel reformers hold some promise of reducing size and providing a reliable source of hydrogen. However, it remains difficult to place an appropriately thin layer of material in the desired geometry to create an effective microchannel reformer. This technology is unlikely to be available commercially within twenty years.

Circuit protection is a problem that remains to be solved in hybrid fuel cell systems: how to protect the fuel cell from load transients and how to protect the load from fuel cell transients. If a fuel cell is the lone electrical source in a system, conventional power supply protection methods should suffice. However, if the fuel cell is incorporated into a hybrid energy system or more than one fuel cell are networked together, the protection issues are not yet solved. The pace of research seems to indicate that this will not be a significant problem in twenty years, however.

Fuel cells as an alternative to batteries is beyond the scope of this investigation. Except for HEV applications, batteries in the expected tactical environment will normally provide less than 500 Watts continuously. Recently, such giants as Samsung and Motorola have found that their plans for cellular communications enhancements are being slowed by inadequate battery capacity. What they develop, perhaps a fuel cell of some sort, could have important implications for mobile electric power if it could be scaled up.

**Indicators of a feasible technology’s existence**

Unlike the turbine and the internal combustion engine, where improvements in technology will improve the performance of already competitive power technologies, improvements in fuel cell technology are needed just to bring the technology to market in the first place. To this end, a study of the press releases of fuel cell companies, small and great, reveals an interesting trend over the past few years. In 1998, nearly every press release announced deal-making and promises. Very few announced products or even prototypes. In the following years, occasionally a prototype would appear. By 2002, the time between these prototype announcements was clearly becoming less and less. The prototypes also became more and more substantial. A strong majority of the press releases still trumpet deal-making and promises, but there is a clear and growing trend of concrete progress. If the content of these press releases is extrapolated to 2015, there will indeed be well-developed hydrogen fuel cell and methanol reformer technologies by then. Having a hydrogen distribution infrastructure by then is questionable. There is little indication that tactical fuel reformers will appear by then. Even if fuel cell technology is feasible by then, there is still little indication that it may be economically competitive by then.

It is not clear whether the rise of HEV technology could be complementary, transitional, or a threat to fuel cell. The fuel cell appears to be developing too slowly to be complementary. The case for the HEV as a threat to fuel cell development is ironically quite plausible. Automobile industry predictions are for a practical HEV by 2005, using an internal combustion engine. The projected pace of improvements to the internal combustion engine could keep it as the technology of choice. Without a market in transportation, it is unlikely that the fuel cell will develop soon enough to be feasible for mobile electric power in twenty years. The transitional case may also be possible if the fuel cell develops quickly enough to supplant the internal combustion engine soon after the HEV becomes established in the marketplace.

The response of the automobile companies may be a good indicator of whether a fuel cell is ultimately feasible for tactical mobile electric power. As mentioned already, there must be some commercial application for the fuel cell. The military lacks the resources to develop it alone. Engine sizes proposed by automobile manufacturers are slightly greater in power rating than those considered in this study (10kW – 50kW for an HEV). The smallest proposed military HEVs are at the upper end of this power range. Fortunately, such fuel cell technology is readily down scalable to about one or two kW. The automobile companies made the decision in 2001 to invest above the billion-dollar level. They have committed to production-ready models in about 2007. They have substantial political support and government investment as well. There is little question that they have a market for any practical fuel cell that they may be able to produce at a competitive cost. If a fuel cell can be developed for the medium power range, then this it most likely will be. However, if the automobile companies fail, then they may give the fuel cell such a “black eye” that it will take decades to recover. One need look no further than the their treatment of the all-electric vehicle to find an example of this.
Conclusions
The fuel cell appears to be a long-term technology. The hydrogen fuel cell already exists commercially, but requires expensive development of a fuel storage and distribution system. A commercial fuel cell with a methanol reformer is quite likely, but it is unlikely that a fuel cell using diesel or JP-8, reformer-based or not, will be available in twenty years. Products are beginning to appear and the trend toward more of them is strongly positive. The response of the automobile companies will be a good indicator of fuel cell feasibility. They should have solid answers before the decade is out.

Thermophotovoltaic
Thermophotovoltaic (TPV) generators use radiant energy to drive a photovoltaic module. In these units, burning a fuel provides radiant energy. This radiant energy strikes a photovoltaic cell, where the energy is converted to electrical form, a direct current. If desired, this dc may be inverted to ac.

TPV has the advantages of silence and size, two characteristics that are quite important in the anticipated tactical environment. Historically, efficiency of TPV systems has been abysmal. However, with the advent of burner designs with better frequency characteristics, improved filters, and better materials for photovoltaic cells, efficiencies have improved significantly. If advances in efficiency continue as they have in the past few years, TPV may have a place as an energy source for tactical mobile electric power within the twenty-year horizon.

Advantages
TPV generators exhibit the following advantages:

Low acoustic noise: The entire energy conversion process is nearly silent. There is some noise from the burner, but it is minor when compared to an internal combustion engine of the same power output.

Weight and size: A 500W unit is comparable in size and weight to internal combustion units of similar power rating. The technology can be scaled upward, but with some difficulty.

No moving parts: The only motion is the flow of fuel, air, and combustion products. Having no moving parts leads to improved maintainability: there are no moving parts to fail. There is some minor stress on parts due to thermal cycling.

Fuels: TPV systems can operate on logistic fuels: JP-8 and diesel fuel. CECOM RDEC has demonstrated such a 500-Watt working unit; Knowles Atomic Power Lab built it.

Heat: Though TPV systems have characteristically low efficiencies, they produce a great deal of heat. TPV systems become more desirable when there is a cogeneration application. Unfortunately, the expected operational tempo restricts this possibility somewhat.

Electrical: TPV units have a direct current output, so there is less power electronics required (for the same reasons as explained for fuel cells). Methods of interconnection are similar to those of PV cells, which are well-known and are addressed in the photovoltaics section of this report.

Disadvantages
Disadvantages of TPV generators include the following:

Low efficiencies: Historically, efficiencies have been 3% to 5%. Much of this may be ascribed to a fundamental mechanism: incompatibility between radiated wavelengths and optimum collector behavior. Recently, a combination of higher temperature differences and better materials have led to improved efficiencies. Claims are near 15%, with 12% having been demonstrated on the bench. As improvements continue in burner design, in filter materials, and in materials for photovoltaic cells, these numbers will rise. The pace of improvements has quickened significantly in the past few years. It is difficult to predict what the efficiencies will indeed be because most of the advancement relies on discovering improved materials. If efficiency rises above 20%, TPV with its size and silence will have a place in the tactical environment.

High temperature: Operating temperatures greater than 1200°C are typically necessary to get a spectrum appropriate for the photovoltaic cells to operate efficiently. This contributes to a significant thermal signature problem. On the other hand, photovoltaic cells must be maintained at a somewhat lower temperature. This requires materials that insulate thermally, but conduct the desired part of the spectrum.

Sensitivity to temperature changes: The spectrum produced by a TPV source is a function of operating temperature. Because energy conversion depends on a degree of compatibility between radiated energy, band pass
filters, and frequency-sensitive PV cells, system performance can be greatly affected by changes temperature. This sensitivity is a subset of the larger issue of full spectral control. Control technology necessary to regulate temperature already exists, fortunately.

Undetermined ruggedness of emitters: Ruggedness has not yet been tested thoroughly. Photovoltaics have not had a reputation for ruggedness. However, some of the newer PV modules are such big improvements and indicate further progress to the degree that this should not be a problem in twenty years.

Scalability: Commercial propane units operate at less than 100 Watts electrical output. CERDEC has a 500-Watt unit working now using logistical fuels. Unfortunately, this may be a technology that is difficult to scale upward. Considering the rate at which units have scaled upward in the past, at most a 2kW unit may be possible within the twenty year horizon. It is uncertain whether any larger individual TPV units may be available by then. A modular approach mitigates this problem, though size and weight suffer with that approach.

Modular solution to upward scalability
Edtech has proposed a TPV unit that operates as an ordinary PV cell by day, but becomes a TPV at night. This reduces dependence on daylight, a common problem of PV energy harvesting systems. The California Energy Commission (CEC) wants 1.1 MW worth of these units. Their solution is modular, a common technique in designing photovoltaic systems. As a result, the CEC’s researchers will address scalability and interconnection issues fairly soon.

Research issues
  Efficiency. Improving the efficiency is the primary research issue. Without a better efficiency, TPV technology will be at an insurmountable disadvantage. Present efficiency levels of 12% are not quite competitive with other technologies. There has recently been a strong trend toward improvement, but further advancement remains dependent on matching the spectrum that is produced to the materials that convert the radiant energy. Therefore, the underlying research issues are spectral control and better materials.
  Thermal signature. TPV units have a significant thermal signature. The close relationship between higher temperatures and operating efficiency does not bode well for mitigating the thermal signature. In applications where the heat can be used, this is less of a problem. However, the anticipated tactical environment does not always have a use for the waste heat. Turbines successfully employ heat recovery, but gain significant size and complexity in doing so.
  Scalability. These units scale upward with difficulty. Nonetheless, even small units may still fit as part of a hybrid power system. For this, they would compete (or cooperate) with energy harvesting. Perhaps a niche may develop for small, portable power, maybe skid-mounted, for loads that can use the heat. Considering the nature of tactical operations as proposed for 2015 and later, it is unlikely that this niche will be large.
  Fuel: Commercial units use propane at present. A 500 Watt unit that uses JP-8 is being developed in 2002. TPV technology that employs tactical fuels should be feasible well within twenty years.

Conclusions
TPV technology provides tactical mobile electric power with the advantages of silence and size. It is being developed to use a range of fuels. In applications where there is a use for its waste heat, a TPV unit is quite attractive. However, its efficiency remains lower than competing alternative technologies. There is a strong trend toward improvement in efficiency, but more work must be done on spectral control. It is also not clear whether TPV technology can be scaled upward to 10kW. Even if TPV cannot be scaled sufficiently upward, it still may fit into a hybrid generation system.

Radioisotope-based Electric Power Generation
Radioisotope generators convert nuclear energy into electrical form. The methods of doing so may be categorized as either thermal in nature or involving the capture of emitted particles. The more effective methods of nuclear power generation in the medium power range appear to be those that are thermal in nature. In fact, most of radioisotope-based electrical generation systems that have reached production are of the thermal type.

Thermal methods take advantage of the heat that decaying radioisotopes generate. Direct current electrical energy is extracted from that heat. Smaller systems typically use thermoelectric methods to extract energy from the heat.
Larger systems normally use a steam power conversion cycle. Because the expected tempo of operations renders steam systems impractical, thermoelectrics are the method of choice for capturing the energy.

Radioisotope systems with thermal energy conversion
In this analysis, the combined radioisotope and thermoelectric system are considered together as a candidate technology for tactical mobile electric power. (A short analysis of thermoelectric systems used with other heat sources is in the next section of this report.) There are several advantages to be gained by using a radioisotope-based system, the most obvious of which is the fact that it can operate without human intervention for 72 hours and much, much longer. For the anticipated tactical environment’s electric power requirements, radioisotope generators have the advantages of silence, ruggedness, and length of service.

**Quiet.** These systems are completely quiet. They emit no audible noise.

**Rugged.** Their history of use in space missions attests to a design for ruggedness. They withstand the forces of a rocket launch without adverse effects. They perform at great extremes of heat and cold.

**Length of service.** Their strongest advantage is their length of service. A radioisotope-based generator meets the power demand for the anticipated 72-hour mission length without refueling. NASA has repeatedly proven that this technology can perform on long-duration missions to remote places. Selecting the appropriate isotope sets the length of service. How to make that selection has been known for decades. Everything is self-contained in a rugged system, providing completely reliable power on demand for hours, months or even years without human intervention.

There are several significant problems with the thermal category of radioisotope systems.

**Duty cycle:** Radioisotope systems are always “on”. They always produce energy at a predictable, nearly constant rate. Gaining more power for peaking requires energy storage, making an already large package even larger.

**Efficiency:** Typical thermal efficiencies for production units are 5% – 7%. NASA Cassini system produces 628 Watts electrical from a 10kW thermal input. Thermal efficiencies of systems being built for NASA Mars missions range from 8.1% to 12.6%, but these operate at 1015°F. Raising the temperature to 1800°F and adding a small amount of cogeneration raises efficiency to 15.6%. For the electric power produced, this obviously creates a great deal of waste heat and a significant thermal signature. Unless efficiency can be improved somewhat, a radioisotope system will not be competitive. It is unlikely that efficiency will improve enough within 20 years.

**Size:** Requirements for shielding and heat sinking lead to a package that is significantly larger than a comparably sized internal combustion engine generator. For example, the NASA Cassini 628-Watt system is the physical size of a 10kW skid-mounted internal combustion engine generator. Typical systems produce about 0.4 to 3.0 Watts / kg, somewhat less than fossil-fuel based systems. Even when the weight of fuel is considered for other systems, this figure is still not competitive.

**Safety:** Safety in handling radioisotope materials is by necessity quite involved. In fact, NASA has abandoned Alkali Metal Thermal to Electric Cells (AMTEC) because of difficulty in handling the materials safely in manufacturing. Handling must be completed far back in the logistic system. This leads to prepackaged modules that require additional security in transit and an individually managed shelf life. Thoroughness in packaging mitigates handling problems at the organizational level if the packaging remains intact. Safety concerns may restrict the acceptable radioisotope materials to those producing only alpha particles, which are much easier to shield. Unfortunately, these tend to have longer lifetimes.

**Industrial base:** There are few companies that can manufacture thermoelectrics and radioisotopes. The economics and politics of the industry make it unlikely that this will improve.

**Public Perception and Acceptance:** Nuclear energy has great public perception problems, too many of which have some factual basis. One need only remember the public reaction to Cassini passing by the earth (but beyond the moon) in 1999 to realize that training soldiers to use this technology will not be as trouble-free as its sealed packaging might suggest. Enemy capture of a radioisotope generator quickly leads to its possible use as a weapon. Due to the properties of typical isotopes, such a weapon is probably more dangerous as a psychological weapon than as a radiological one.

Particle-based generation
The other category of radioisotope electric power generation is particle-based methods. Of these, alphavoltaics require only minimum shielding. Alphavoltaic generators surround the radioisotope with a semiconductor material. Alpha particles invade the crystal lattice of the semiconductor material and create hole-electron pairs. These holes
and electrons are captured in a manner fairly similar to that employed in a photovoltaic system. These systems provide the advantages of quiet power on demand at extreme temperatures for long periods of time.

Prototype particle-based systems tend to be quite small, though this may be simply a function of the fact that most units are individual cells built for research purposes. Cells can be interconnected. Whether these units can be scaled up to medium power range is unknown. Even if they are scalable, their energy density compares somewhat unfavorably with their thermal cousins as well as internal combustion engines. In other words, a 628-Watt particle-based system would be even bigger than Cassini’s thermal system. Addressing the issues of scaling upward does not appear feasible within a twenty-year time horizon.

Research trends
Isotope behavior and handling is an established science that has been thoroughly catalogued. Most of the recent advances and ongoing research have been concentrated in heat engines, primarily thermoelectrics. The search for new thermoelectric materials has yielded some significant improvements in the past few years, particularly in lifetime, conversion efficiency, and reduced magnitude of waste heat.

The primary technical problem with alphavoltaic systems is their propensity to destroy the semiconductor crystal lattice. Alpha particles lodge within the lattice, disrupting its ability to absorb more particles in the same vicinity. Useful life of such a system is thereby reduced, though this should not be a problem for 72 hour combat missions. Materials, such as icosahedral borides, seem to absorb the alpha particles with minimal damage to the lattice. Research is continuing, but this technology does not appear to be feasible within a twenty-year horizon.

Thermoelectric energy conversion systems for other heat sources
Thermoelectric systems, as discussed in the previous section, are a common means of generating energy from the heat produced by decaying radioisotopes. In fact, thermoelectric systems can use any temperature differential to generate electric power. In the power range above 500 Watts, practical units draw heat energy from either radioisotope decay, as discussed above, or fossil fuels. The former are more efficient because they have no hot exhaust gas stream. Thermoelectric units also are used for energy harvesting. However, in a size that would be comparable to a 10kW internal combustion engine generator, these energy harvesting units generate much less than 500 Watts.

An example of a fossil fuel thermoelectric generator is a Teledyne system produced for the Army in the 1980s. It burns any fuel from kerosene to diesel, providing 191Watts at 24-36Vdc for 12 hours. Its microprocessor-based controls closely regulate the unit and it has a rugged construction. It does produce 2500 Watts of heat, a great thermal signature. Though it could be scaled up, the thermal signature and poor efficiency make that possibility unattractive.

Thermoelectric units become perhaps practical when their waste heat is employed productively. An example is a self-contained 2.9kW space heater. It provides its own electrical supply for its advanced operating controls and safety measures. It is silent, except for a small fan. However, electrical output is quite small, less than 100 Watts and most of that goes into housekeeping.

New materials are expected to continue to dominate any advancement in thermoelectric conversion. These have led to significant improvements in efficiency, with prototypes exhibiting efficiencies up to 12.6%. The combination of low efficiency and great thermal signature for its size render thermoelectric systems impractical for tactical mobile electric power in the 500 Watt to 10 kW range. NASA and Teledyne have been conducting this research. The research is proceeding at a slow pace and is unlikely to yield anything to compete with the internal combustion engine or turbine by 2015. There may be some potential for inclusion in a hybrid system.

Conclusions
Radioisotope-based generation converts energy released by radioisotope decay into electrical energy. Thermoelectric systems that convert the heat from radioisotope decay are more practical than particle-based methods of energy conversion. Radioisotope-based systems do have one great advantage: they can provide electric power for a very long time without human intervention. However, its size, efficiency, and adverse psychological effects, among other disadvantages, render it impractical. Thermoelectric systems, of course, can be used with any
temperature differential to generate electric power. However, their efficiency is poor. Research is being performed primarily into identifying and understanding new materials for thermoelectric systems. This is proceeding slowly and is not likely to produce results that are competitive within twenty years.

**External Combustion: Stirling Engine**

Stirling engines are “external combustion” engines. A Stirling engine uses a heat source to raise the temperature of a sealed working fluid, pressurizing internal cylinders and moving a piston. The heat source is a continuous flow external burner. Stirling engines enjoy the reputation of being clean, quiet, and highly efficient. They were used extensively for industrial applications until replaced by internal combustion engines nearly a century ago. Recently, advances in metallurgy have allowed the development of components able to withstand the high temperatures necessary to restore the Stirling engine as a viable technology. They can be readily manufactured in the 500 Watt to 10 kW power range. Current commercial applications include commercial submarine propulsion, cryocoolers, and classrooms.

**Advantages**

A Stirling Engine has a number of attractive advantages for tactical mobile electric power:

- **High efficiency:** Stirling engines typically run at efficiencies of about 30% - 40%. These are numbers from commercial models over a range of a few watts up to 3MW. This is currently better than all competing technologies except the fuel cell.

- **Multifuel:** Stirling engines can be designed to efficiently use commercially available fuel. The fuel burns outside the sealed working fluid and cylinders, hence the term “external combustion engines”. Therefore, the fuel burn tends to be more complete than obtained by an internal combustion engine. Emissions are low, but not as low as the fuel cell produces. Performance of an external combustion can be more easily optimized for the load.

- **Quiet:** The combustion and energy transfer process is characterized by less noise and vibration than an internal combustion engine or turbine. There are no large, pulsed variations in fuel burn. There are no turbine blades in the stream of combustion products. It has been found that back-to-back mountings of Stirling devices reduce their already lower levels of vibration. Their quietness is a strong factor in their use in submarines.

- **Low maintenance:** Sealed Stirling engines require only minimal maintenance on the burner system, making them nearly maintenance-free.

- **Long Life:** Sealing dramatically improves the life of a Stirling engine. Contaminants do not enter the working fluid. The ratings of most sealed Stirling systems exceed 50,000 hours (5.7 years continuous). This is slightly better than the life expected of a microturbine and much better than any other competing technology.

- **Emissions:** The more complete, controlled burn that is consistently possible for a Stirling engine means fewer emissions overall and fewer NOx emissions in particular.

**Disadvantages**

The Stirling engine’s disadvantages are as follows:

- **Slow response:** A Stirling engines takes several minutes to start. It changes its power output level in a similarly slow fashion. This is much worse than a microturbine or even a fuel cell. They are not “power on demand” machines. This means that they need a lot of energy storage to obtain a bandwidth competitive with other technologies. The major automobile companies did build automobiles with Stirling engines in the 1970s. However, customers were discouraged by the slow startup and poor acceleration.

- **Heavy:** Typically, Stirling engines have somewhat less power density than internal combustion engines, typically by a factor of 1.5 or greater. Moreover, the relative pace of research advancements in favor of the internal combustion engine is actually widening that gap. Adding energy storage to improve the response to load changes makes its weight disadvantage even worse.

- **Exacting manufacturing methods required:** These include use of exotic materials to contain high temperature fluids.

- **Industrial base:** With only a few niche markets, no industrial base currently exists. Given the failure of substantial efforts to introduce a Stirling automobile in the 1970s, efforts to create a production base will meet resistance.
Research issues
There has been no shortage of programs to investigate the Stirling engine. However, few have succeeded in finding a niche for it.

The Stirling engine remains in advanced development for an automotive engine. However, finding and working with materials to withstand the high temperatures is a problem. Today’s efforts do not display the urgency that they did twenty years ago.

Hydrogen is the best working fluid. It has a high specific heat and is available in large quantities. However, it is difficult to contain hydrogen in a working engine that is known for its high temperatures. Problems in so doing have not yet been completely solved.

The National Renewable Energy Laboratory (NREL) is abandoning Stirling in its biomass systems in favor of microturbines: fuel, life, maintenance, and emissions are comparable and response and weight of the Stirling is somewhat poorer. No one has yet found a Stirling engine to be competitive with a diesel engine or gas turbine for power density, response, and capital cost. Because research investment is somewhat lopsided in favor of diesels and turbines, it is unlikely that situation will change in the next twenty years.

Conclusions
For mobile electric power, a Stirling engine has the advantages of high efficiency, low acoustic noise and a multifuel capability. It is a known technology that can be manufactured in its present form. However, it is not a “power on demand” machine. Its weight and the additional energy storage necessary to make its performance competitive for mobile electric power are significant problems. The failure of automobile industry efforts to produce a Stirling automobile in the 1970s remains in the institutional memory. Incremental advances in materials may occur in the next twenty years, but it is unlikely that Stirling engines will be used much outside of their present niche.

Energy harvesting
Energy harvesting includes a number of technologies: wind, photovoltaic, biomass, human, hydroelectric, wave and tidal, and geothermal. They are termed “harvesting” because the energy is ubiquitous when available, and, in most cases, its availability varies periodically in time by location.

Hydroelectric, wave and tidal, and geothermal
The latter three technologies are generally impractical in the expected operational environment and tempo. To gain 500 Watts or more, the physical plant must be stationary. That is impractical for the expected operational requirements. Therefore, these will not be addressed further.

Human
Peak power output from a single human is typically less than 200 Watts. Continuously sustainable power output is under 40 Watts. Because this report considers only generation above 500 Watts, human sources of power will not be addressed further.

Biomass
Biomass is the second most common renewable energy resource used in the US to generate electricity. It accounts for 38% of the electricity generated from renewable sources, second only to hydroelectric sources. Applications include incineration of garbage and recycling of landfill gas. These are large system whose technology has been available for a couple decades.

An efficient, compact, and portable method of processing of biomass is fluidized bed technology. Plant material is chopped finely and the augured into a fluidized bed of sand and hot air. In fact, almost any combustible organic material can be so processed. The heat produces methane, a gas having a fairly low energy content. This methane is collected and pressurized, then burned as gaseous fuel in a microturbine, for example. Preparation of biomass (collection, chopping and augering into the fluidized bed) is an equipment-intensive process, as is collection of the methane gas. Efficiency estimates range to widely to make an accurate determination.
A biomass system in the medium power range requires a comparatively large physical plant, for example, about 15 cubic meters to store and prepare biomass for a 20kW system for 48 hour of operation. Systems at this power level are still in development, being estimated for production by 2008 at the earliest. They do not further scale down well.

Given the anticipated operational tempo, biomass is impractical for tactical mobile electric power. Perhaps the only type of operation that could effectively use a biomass electric generation system is Stability and Support Operations. For example, portable biomass systems have been installed in remote tropical areas. NREL is currently evaluating the cultural effects of such installations. Therefore, in remote locations having significant amount of biomass, such a generator could be effectively used for a camp or station. Eventually turning it over to the host nation is a possibility, provided an effective maintenance program precludes premature failure. Nonetheless, doctrine requires rapid transition among the seven categories of operations, rendering biomass impractical for tactical mobile electric power.

**Photovoltaic**

Photovoltaic (PV) systems use semiconductor materials to convert light into electricity. To gain 500 Watts or more, the light source must either be sunlight or the radiant energy emitted from a burner. The latter is known as thermophotovoltaics (TPV) and is discussed elsewhere in this report. PV has the advantages of favorable signature characteristics for acoustic, infrared, and (if their control electronics are designed properly) EMI. They give reliable power on demand when sunlight is available. PV systems are easily scalable. Unfortunately, PV has significant difficulties with energy density, efficiency, mobility, and visible signature.

Ongoing research efforts tend to concentrate on the following: lowering the cost, developing more efficient materials and more effective device designs, expanding production capacity and rates, and improving product quality.

**Lowering costs:** Costs have decreased tenfold in the past decade to about $5 per watt. Further reductions in cost are expected to cut that figure in half over the next twenty years. Even that is still quite expensive.

**Developing more efficient materials:** Efficiency is in the range of 10% to 15% for practical materials today. Predictions vary widely and unrealistic claims abound, but an evolutionary trend should bring efficiencies to 14% to 20% in twenty years.

**Developing more effective device designs:** The best advertised of these include shingles and siding for buildings. For military use, flexible lightweight panels are easier for the soldier to move and install. Lighter weight has been a big improvement in photovoltaic cells over the past decade. A prototype flexible, 150 square centimeter, solar tarp already exists. Scaling it upward should be done within a year or two. A 9x12 tarp could produce about 1.5kW peak under sunny conditions. Further advances in packaging will improve this even more. Selective light filters can now create camouflage patterns on the cell surface instead of the bluish tone that is ubiquitous in most of today’s designs.

**Expanding production rates:** About 300MW in capacity is produced worldwide in 2002. Because PV is expected to remain the most expensive renewable for the next two decades and beyond, growth rates will be fairly moderate, about 5% annually.

Photovoltaic systems, as energy harvesting equipment, require energy storage at night and on cloudy days. As a result, peak generating capacity must be at least three times greater than average consumption. Storage capacity must cover every night and the worst anticipated weather. A promising combination of photovoltaic systems with TPV is being developed in California and should be available within the time horizon. These issues are addressed in the energy storage and TPV sections of this report.

PV was considered for military power generation in the 1970s, when power electronic converters initially became practical. Some prototypes were built. Unfortunately, 500 continuous Watts required at least fifteen square meters. When assembled from its two-ton trailer mount, the converter equipment and battery storage on the trailer appeared to be inside its own oversized, heavy solar carport. At projected efficiencies for 2015, a 500-Watt system needs about six square meters and weighs less than a ton with batteries. For comparison, the footprint of a HMMWV is about ten square meters. Nonetheless, that is still somewhat impractical as a primary power system for most of the anticipated tactical applications. PV could serve in a hybrid system, a possibility discussed as distributed generation below.
Wind

Wind power systems convert the kinetic energy of the wind into electricity. Of the renewable energy sources, wind energy has made the most progress in the past decade. Its price is now competitive with fossil fuels: 4-6 cents per kW-hr. Capital costs are less than $1 per watt. This is testimony to what a decade of significant investment can do. It appears to remain the most economical form of renewable energy for at least the next three decades and beyond.

Most wind turbines have a horizontal axis configuration with two or three blades, a drivetrain including a gearbox and generator, and a tower to support the rotor. A typical 1kW system has blades ten feet in diameter and weighs 65 pounds. For tactical use, these dimensions are awkward at best. Obviously, it is dependent on the wind itself, so expecting a reliable “power on demand” is not reasonable for the anticipated range of operations. As with most other renewable energy technologies, wind power would probably work for Stability and Support Operations, but not for other anticipated operations.

Recent research addresses aerodynamic efficiency, structural strength of blades, variable speed wind generators with power electronic controls, and taller towers. For any given speed and blade design, there is a peak power point. The advent of information-based control technologies applied to power electronic converters now allows wind turbines to run at this peak under variable speed control while supplying a fixed frequency electrical grid. The have a respectable response to rapid changes in load. This capability has been available for more than ten years and is being improved continuously. New blade designs made with better materials have dramatically increased output capability. Taller towers have been built to take advantage of faster winds further above the earth’s surface. The Europeans, especially Denmark and Germany, are well-capitalized and have invested greatly in wind turbines. They project costs at 2-4 cents per kW-hr by 2015. Their installed capacity is growing by 35% annually, much of it in offshore installations. China already has over 100,000 small turbines generating electricity and pumping water remotely. US companies have reduced their overall funding and have no large companies in the wind energy business anymore.

Wind power equipment, though transportable, does not lend itself to rapid movement and installation. Its energy density is somewhat less than fossil fuel generators. Because wind is not always available, energy storage is necessary. This combination of equipment that is awkward move and install, unfavorable energy density, uncertain availability of the resource, and a significant requirement for energy storage leads to the conclusion that wind energy will remain impractical for tactical use as a sole source of mobile electric power. It may be appropriate as a component of a hybrid system.

Energy Harvesting Research as a Source of other Technologies

Though apparently disappointing for tactical mobile electric power, energy harvesting technologies do contribute important some developments that merit attention. Variable speed generation through the use of power electronics was originally developed in the wind industry. A wind turbine’s power electronics are directly applicable to variable speed generation regardless of prime mover. Fast, effective control of a peak power point is a reliable technology that was developed in the photovoltaic industry. Fuel cells have adopted that technology. The inadequacy of Stirling engines in using low-quality gas produced from biomass encouraged the turbine industry to use that fuel. Therefore, these energy harvesting technologies, though unsuited as sole power sources for the task at hand, do contribute significant enhancements to the knowledge base. It is wise to search occasionally for such developments and adapt them as they occur.

Hybrids

Though energy harvesting appears to be insufficient to provide the levels of power required for tactical mobile electric power, the hybrid systems containing energy harvesting components should not be overlooked. A sustained 72-hour requirement is in the first sentence of this report’s vision statement. Most power generation technologies can be enhanced by adding generation from an energy harvesting source. Perhaps we can wring out only a few extra hours worth of energy. Considering how difficult it is to get 72 hours from most power technologies, even a few hours’ relief can be quite valuable.

Hybrid systems have been proposed and built in the past. For example, a hybrid diesel generator, PV, and wind system was built at Fort Huachuca in the early 1990s. The National Renewable Energy Laboratory built a diesel
generator, PV, and wind system interfaced to the public utility in 1998. The California Energy Commission has funded a hybrid of sorts by combining PV and TPV for a 24-hour capability. On the small end of the scale, NASA has a “power tile” that consists of a chip containing the following layers, from top to bottom: PV cell, thermoelectric generator, and thin film battery. There are a host of other examples that one could cite, many of them proposed within the past decade or so. Most of these hybrid systems are impractical for the tactical environment that is anticipated, but some of their underlying concepts may be useful.

A hybrid system must provide additional energy without bringing along too much “baggage”. “Baggage” may mean more equipment that adds more weight and detection risk, for example, or problems of coordination and control. Such systems have only become practical recently because the signal processing and control capability has only recently become affordable for smaller systems. Coordination of more than two or more forms of generation has become a technology in itself. It is sometimes known as distributed generation because it is usually employed at remote sites, distributed in various places on (or even off) the electric utility distribution grid.

Distributed Generation
An interesting and fairly recent set of developments from the renewable energy industry is improved methods of distributed generation. Distributed generation is defined as interconnected modular electric generation or storage located near the point of use. Generators and storage may be of different types or more than one of the same type or any combination thereof. They may be connected to the utility grid or independently operated off-grid. Those connected to the grid are interfaced at distribution level, usually by power electronic converter. By design, distributed systems should provide high value energy, capacity, and services such as voltage regulation, power quality improvement, and emergency power.

Distributed generation has become a topic of research interest in the utility industry, driven by deregulation and restructuring. California’s rolling blackouts of 2000-2001 added some incentive for distributed generation and some examples of it. The general problem is to build a simple, perhaps Internet-based, system for dispatching multiple distributed generators. In fact, the Electric Power Research Institute (EPRI) has specified this as its #2 goal for the next decade, right after broad implementation of power electronic systems for monitoring and control of the power delivery system. The National Renewable Energy Lab (NREL) is leading the effort to write the standards, so renewables and hydrogen storage will be included. If these research efforts prove fruitful, distributed generation will improve the Army’s ability to take advantage of host nation electric power resources. In other words, distributed generation methods would allow use of a host nation electric grid, but at substantially reduced risk to sensitive equipment of the ill effects of interruptions, surges and sags, and switching transients.

Public utilities must resolve several technical, financial, and management issues. In the case of military applications, the issues are primarily technical. Fortunately, the Uninterruptible Power Supply (UPS) industry has the necessary technical resources already. These are primarily advanced control methods of control, interfacing, and circuit protection. There is certainly no technical barrier to having distributed generation technology available soon for electric power generation. Unfortunately, the history of the public utilities in addressing coordinated financial and management issues of this nature has been mixed. Nonetheless, it is likely that advanced methods of distributed generation will be commonplace by 2015. Methods to protect the distributed generator from the utility system and vice versa will also be well known by then. All will be controlled with embedded systems at the point of application, linked to a high-level controller at the utility. The technology to do so already exists; standards are being written; and design short courses have begun to appear at the leading universities. This is the same technology that will allow networking of generators at a tactical site, greatly improving the reliability of tactical mobile electric power.

Conclusions
For tactical applications of 500 Watts or more, energy harvesting will remain impractical as the primary source of energy. Other power technologies have significant advantages for the intended applications. Energy harvesting may serve as a supplement, however. Technology enhancements developed for energy harvesting may apply to other mobile electric power technologies and should be actively identified. Distributed generation technology provides the means to incorporate energy harvesting into a power system. It also gives the opportunity to tap into host nation support with enhanced reliability and better power quality. Advanced technology for distributed generation already exists in the UPS industry and will enhance the reliability of tactical mobile electric power.
Chart

On the following page, Figure 1 a comparison of the various technologies. Comparison numbers (on a 0 to 10 scale) are assigned in accordance with the analysis described in this section. Color coding shows relative comparison as well. Each criterion is weighted equally and a subtotal is obtained for each technology in each force design principle. Summing weighted subtotals for each force design principle leads to a weighted total for each technology. Weightings are listed by each criterion and force design principle and can be easily changed in a spreadsheet version of this chart.
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Figure 1. Comparison of Power Technologies
Section IV

Energy Storage for Mobile Electric Power

An alternating current system moves energy electrically but, unfortunately, cannot store energy electrically. Instead, energy in an ac system may be stored in the following forms: electrochemical, electromagnetic, kinetic, or as potential energy. Important considerations include energy density, the amount of energy to be stored per unit mass, and power density, the rate at which energy can be added or removed per unit mass.

**Batteries: electrochemical energy storage**

To match the cyclic and stochastic availability of an energy source to the different cycle and stochastic character of a load, batteries are an attractive means of energy storage. For example, microturbines use them to ride through rapid changes in load. Energy harvesting technologies, such as wind and PV, employ them against occasions when the wind isn’t blowing or the sun isn’t shining. Unfortunately, their weight and volume makes it unreasonable to use batteries alone, either primary or rechargeable, to provide electrical power at levels of 500 Watts to 10kW for 72 hours at the expected operational tempo. Therefore, this analysis will consider batteries as an energy storage element within a mobile electric power generation and storage system.

Electrical generation systems need batteries that can both store and release energy. Therefore, the discussion in this report is limited to rechargeable batteries. The currently dominant technologies in rechargeable batteries are Lithium Ion, Nickel Metal Hydride, and Lead Acid. Research is proceeding into lithium polymer batteries, with marketable products expected in about five years. Metallic lithium batteries are being investigated, but they have difficulties in recharging that will probably keep them from the market within twenty years.

Lithium Ion batteries currently provide approximately 170 Wh/kg. Predictions for improvement of these batteries in twenty years are 200-300 Wh/kg. They are lightweight and offer excellent power density and efficiency, making them favored for the small portable market, electric vehicles and other applications that require power pulses. Lithium ion batteries do require greater care in handling and in avoiding overcharging.

Nickel metal hydride batteries provide approximately 100 Wh/kg. Predictions for improvement of these batteries in twenty years are 120-150 Wh/kg. They offer good power density due to their good ionic conductivity of the potassium hydroxide electrolyte. The major challenges are their high cost, the need to control hydrogen loss, and their low cell efficiency.

Dry lithium polymer cells are anticipated by 2007 to have an energy density of about 200 Wh/kg and to run 1000 full cycles. A gelled electrolyte lithium polymer battery is also expected in volume production in about five years. These gelled electrolyte lithium polymer batteries have gained the name of “pouch cell” due to their packaging. Their flexible, heat-sealable foil package gives them a flexible form factor improves an already light weight. Swelling remains a problem, caused by gas generation during charging and discharging. Manufacturers insist that gas generation is not a problem when charged at correct current levels and kept within specified voltage levels. Lithium polymer cells tend to be more resistant to overcharge than lithium ion cells.

Lead acid batteries have the advantage of volume production and lower cost. These batteries are currently used at most electric utilities for backup power to restart large synchronous generators. They have an energy density up to 45 Wh/kg. They are heavy and have a short life, but do have good power density. The sealed lead acid (VLRA) batteries are maintenance-free and more robust. Gel batteries are a variant that is robust and can take some heat, attitude, and charge abuse. Some small improvement is expected in the next twenty years, but not enough to significantly challenge the other types of batteries mentioned above.

Increasingly, “smart” battery technology will become available. These have internal sensors and electronics to indicate state of charge, temperature, voltage, current, etc. Datalogging of this information enhances system troubleshooting capabilities, giving the user important information, such as a “gas gauge” and inputs for maintenance diagnostics, both on-site and remotely. The SMbus standard is designed to provide for serial transmission of this information. The automobile industry will go to 42-Volt technology over the next decade. In so doing, more pieces of information about battery performance will be sensed. These will be integrated into on-board diagnostics to provide a more comprehensive picture of battery performance and how it affects system performance, including for example, on-board communications, infotainment, navigation, computing, and
safety systems. Some of these will appear in “driver’s seat diagnostics”, particularly on higher-end automobiles. Such an information-based approach has also been proposed for “smart” circuit protection that would reduce the number of fuses. Dual battery systems are also being considered: a 42-Volt battery with a thin-metal foil technology for lots of power and a second battery with more bulk for capacity. Because a 42-Volt system has a number of cells in series, some have proposed smart switching of cells to improve battery life. The capital cost will probably delay or defeat that idea. These improvements will all appear on automobiles within ten years. Every piece of this technology would be available to tactical mobile electric power if desired.

**Ultracapacitors: electrostatic energy storage**

Capacitors have long been used to store energy for applications requiring a great deal of power but relatively little energy. In other words, they can respond with a limited amount of energy in a very short time. Their most common applications include filtering, providing a limited disturbance ride-through capability, pulsed power, and reactive power generation. When used as a companion to a battery or generator, capacitors provide instant “power on demand” until the greater energy capacity of the battery or generator is able to assume the load. Several advanced capacitors that are in development promise greatly improved energy densities.

Ultracapacitors, also known as supercapacitors, are electrochemical devices that store electrical energy in a double layer of ions. This gives a capacitance and an energy density far exceeding that of “conventional” capacitors, such as electrolytic, tantalum oxide, or oil. Capacitance values are thousands of farads, nearly a million times the capacitance of similarly sized “conventional” capacitors. They deliver bursts of high power and can charge rapidly from most energy sources. Energy densities are about 10% of a lithium ion battery, but ultracapacitors have ten times the power density and more than 100 times the cycle capacity. Efficiencies are typically 85% to 98%, better than most batteries. They operate in a wide range of temperature and humidity. They can store a charge for more than ten years, also better than most batteries. Their primary disadvantage is a low terminal voltage rating, typically 2.5V.

A great deal of progress has been made on ultracapacitors in the past few years. The power quality industry has become their primary niche and will remain so for the foreseeable future, providing energy storage for a short-term ride-through capability. For example, an HEV equipped with ultracapacitors has somewhat greater range and greater battery life because ultracapacitors are more efficient in capturing and releasing energy from braking and acceleration over hundreds of thousands of charge/discharge cycles. If used with internal combustion or turbine generators, they mitigate short disturbances, allowing more sensitive electronic loads to be employed.

Hypercapacitors are another advanced capacitor having similar advantages. These have a voltage capacity of up to 1.0kV and exhibit low equivalent series resistance. However, they do not have the energy density of ultracapacitors and their performance degrades in warm weather. They appear to be suited for use as dc link capacitors. In the next twenty years, hypercapacitors will see further improvement in their strong points and will perform well under cryogenic conditions.

**Flywheel: kinetic energy storage**

Flywheels store kinetic energy. A rotating mass driven by a motor with a variable speed drive system is the most common configuration. Though flywheels have been used for centuries, recent advances in topology and materials have significantly increased the amount of energy that they store.

Flywheels naturally produce high power in a fairly small space essentially on demand. They charge and discharge rapidly. They exhibit little sensitivity to operating temperature or discharge patterns. They require less maintenance than lead acid batteries, but more than lithium ion or nickel metal hydride batteries. Commercial packages integrating them with diesel generators are quite common. Their commercial capacity range is from 500 W·hr to 500 kW·hr. Power densities are approximately 200 W·hr/kg, a figure quite competitive with batteries. Most commercial systems are designed to discharge in about a minute. The speed drive system’s components have peak current and voltage limits; those provide the power density limit.
Recent advances in composite materials technology have produced flywheels that rotate above 100,000 RPM with tip speeds in excess of 1000 meters/second. Magnetic bearings and vacuum enclosures reduce losses to about 0.1% of stored energy per day. Advances in variable speed drive control technology enable counterrotating flywheels to greatly mitigate the gyroscopic effects. Despite significant progress recently in creating safe failure modes to contain a failed flywheel at these speeds, enclosures must still be quite strong. This increases weight and cost. Unfortunately, the combination of composite materials, advanced bearing technology, variable speed drives, and inertial containment yield a cost much higher than competing energy storage technologies.

There are three primary markets for a flywheel system: continuous power, power quality, and battery isolation/redundancy. Continuous power systems back up a utility grid with a diesel generator. Flywheels or batteries provide transition to the generator. Power quality systems use a flywheel or batteries to smooth out sags and interruptions, most of which are less than a second long. Battery isolation/redundancy systems use a flywheel to reduce the number of battery charge/discharge cycles.

The research trends are toward building ever larger systems and toward factory-assembled complete packages, having carefully designed and optimized materials and electronic inverter drives and controls. Centrifugal force in flywheel systems is directly proportional to energy stored, so any improvement in strength of materials translates directly into a proportional increase in energy density. Any improvement can be easily leveraged for smaller flywheels, such as those appropriate for tactical mobile electric power. Improvements in power electronic devices will increase the power density of the inverter drive system. For these devices, power handling capability has increased by a factor of 20 in the past five years; similar improvements are expected in the next 20 years. This is particularly important for rapid current response, giving the ability to better handle demands for pulses of power. Further reduction in losses will be achieved, though these are exceedingly small already. Because power quality events often correlate to weather and load characteristics, commercial flywheel systems will soon have information processing quite capable of correlating inputs from load sensors and from data files through an Internet link to modify the flywheel’s energy state and its control system response in real time. It is unlikely, however, that flywheel systems will have a price comparable to batteries within twenty years.

**Superconducting magnetic energy storage**

Superconducting magnetic energy storage (SMES) uses a low-temperature coil to store energy inductively. At cryogenic temperatures under a range of current and magnetic flux density, some materials lose all electrical resistance. A current will flow in these superconducting materials without any loss of energy. In SMES systems, this current is made to circulate in a superconducting coil, storing energy in a magnetic field. Control of this current is normally by means of a power electronic converter. Charge/discharge efficiency is typically greater than 95%. Energy can be delivered within a microsecond of a request with delivery lasting for a few seconds up to several hours, depending on what is requested and how much energy is stored.

Design of SMES includes the following considerations: Coil configuration, energy capability, structure, and operating temperature. A compromise relates these considerations to the parameters of energy/mass ratio, Lorentz forces, stray magnetic field, and energy losses to achieve a reliable, stable, and economic solution. In SMES, coil components and refrigeration capacity dictate energy density; the design of the power converter dominates power density. SMES systems have a reputation for being quite heavy and costly. Iron core coils, a power converter with its own energy storage requirements, refrigeration equipment, and containment of cryogenic fluids all contribute to system weight. Low temperature SMES (~4°K) are already in production; high temperature SMES (~77°K), having significantly less refrigeration losses are still in development. The latter is likely to be in production long before 2015.

To become competitive for energy storage in mobile electric power systems, SMES will require a breakthrough in superconducting materials. For any technology, breakthroughs are notoriously difficult to predict. SMES is no exception. Nonetheless, SMES bears watching if such a breakthrough occurs. In fact, much of the ongoing research in SMES assumes a breakthrough and then addresses the issues that appear in the process of exploiting it. Consequently, over the next twenty years and beyond, much of the evolutionary research in SMES will be in developing tools and supporting technology: high speed controls, sensors, power conversion, etc. In SMES
research, improvements often are leveraged from other technologies. For example, switching technology applied to improve the power density of SMES systems originally appeared as a means of gaining better power density from batteries. The same technology has since been applied to ultracapacitors for similar purposes. Therefore, to find developments in SMES that apply to mobile electric power applications, the most likely place will be where technology that can be leveraged appears: in the power quality industry, such as Uninterruptible Power Supplies.

Battery manufacturing is a mature industry. There are likewise several manufacturers for the various kinds of flywheels. Unfortunately, the manufacturing base is still rather sparse for SMES. When compared to batteries and flywheels, SMES is a technology that has far fewer units in operation and has a much smaller market. Even if the appropriate breakthroughs occur, it will take awhile to build up the manufacturing base and to incorporate the developments found in supporting research.

**Pumped storage: potential energy storage**

Potential energy storage is another common means to store energy. The most popular means are based on pumped fluid, usually water or air. Pumped water systems raise water to a height above a turbine and recover energy by returning the same water through the turbine. Unfortunately, to gain sufficient energy capacity, pumped water systems are immobile. Compressed air systems store energy by compressing air inside a large volume. If compressed air were an answer, then it would seem more economical and productive to compress hydrogen instead. For the anticipated operations tempo, pumped storage systems are likely to remain impractical.

**Energy storage application capabilities**

The power density for each type of energy storage and the typical maximum duration of use are shown in Figure 1. This is a convenient way to represent the concepts of power density and energy density. The chart is designed for UPS applications, hence the terminology for various groups of applications:

- **Power quality:** Stored energy is applied only for seconds or less as needed to assure continuity of power. This would include mitigating sags and providing ride-through for brief outages, a capability required for tactical mobile electric power when the underlying generation technology cannot provide fast enough response. An example is the batteries that overcome the slow step response of a turbine or fuel cell.

- **Bridging power:** Stored energy is applied for seconds to minutes to assure continuity of service when switching from one source of energy generation to another. This would cover longer outages and include HEV applications. For example, batteries provide bridging power in many hybrid applications of wind power.

- **Energy management:** Stored energy provides sufficient time to decouple the timing of generation and consumption of electrical energy. Load leveling is a typical application, allowing the user to operate independently for many hours. An example is using batteries to gain continuous power from a PV. Unfortunately for tactical mobile electric power, technologies such as hydro and compressed air storage and flow batteries are impractical.

**Conclusions**

Energy can be stored by various means: chemical batteries, capacitors, flywheels, superconducting magnetic energy storage, and pumped storage. Each has its own capability for energy density and for power density, as shown in Figure 2. For mobile electric power in the anticipated tactical environment twenty years hence, rechargeable batteries appear to be the strongest alternative for energy storage. Flywheels have some attractive characteristics, but will remain more bulky and expensive than batteries. SMES is likewise heavy and expensive, awaiting a breakthrough in superconductors that reduces the refrigeration requirement. Hybrids, such as battery-capacitor combinations, will become more attractive as they improve the responsiveness of energy storage systems while maintaining the capacity.
Figure 2. Capabilities of Energy Storage Systems

Section V
Performance Enhancements

Introduction
Sections III and IV present power generation and energy storage technologies, respectively. There is a host of technologies that enhance performance of power generation and energy storage. They are called enhancements in this report because improvements in these technologies enhance the performance of more than one power generation or energy storage technology. Among the more promising enhancements are the following, each of which is addressed in more detail in this section of the report:

- Power management, as described in the vision statement
- Hybrid electric vehicle technologies
- Uninterruptible power supply technologies
- Fuels
- Selection of electric machine topology
- Power Electronics
- Advanced nonlinear control
- dc microgrid technology
- Protection of networked generators: efficiency and redundancy
- Server load

This section ends with a brief mention of few other issues and technologies that may become significant.

Far greater than any of these individual enhancements will be the effect of advances in information technology. On a grand scale, advances in information technology lead to a similar transformation of the legacy force into the Objective Force. Information technology will likewise revolutionize the effectiveness of tactical mobile electric power. These changes are significant enough to merit their own section, Section VI of this report.

Some of these enhancements have already received mention in this report. In this section, more detail is presented on how these issues or technologies will affect tactical mobile electric power generation and energy storage. Obviously, this list is not exhaustive nor is the coverage comprehensive. However, these are among the more significant.

Power Management
The second paragraph of the vision statement emphasizes power management. This technology enhancement has significant potential for stretching the amount of power available from a given configuration. It also may be a vehicle for introducing new technologies.

In both long term and short-term solutions, the key to advanced and alternative power sources is power management. This power management must efficiently tailor power output to load over wide ranges. It must also produce a generating device that provides the minimum necessary power only on demand, may increase operation time, decreases the logistics footprint, and reduces total ownership cost.

Definition
Power management is defined as minimizing power consumption by using power only when necessary and then only in the most efficient manner. Power management may be characterized in two categories:

- **Dynamic power management** is making real time decisions to minimize energy consumption. It involves paying attention to power consumption as it occurs, using power only when necessary and then only in the most efficient manner. The load’s electronic system’s software performs dynamic power management as it governs system operation. Dynamic power management also occurs when operators intentionally take measures to reduce unnecessary power consumption. Software coding and operator training are important vehicles for achieving effective dynamic power management.

- **Static power management** is designing hardware and software with energy conservation as a design criterion. Care is taken to identify and optimize tradeoffs that occur between performance and energy consumption. Design and policy are vehicles to achieve improvements in static power management.
How energy losses occur

An insightful way to estimate electrical power losses in switching semiconductor devices is to realize that a certain amount of energy gets stored in the device’s output capacitance when the device is energized but does not conduct (i.e., the device is OFF). When the device is triggered into conduction (turned ON), this energy becomes heat and dissipates. Energy storage is computed from the familiar $\frac{1}{2} CV^2$ expression, where $C$ is the device output capacitance and $V$ is the OFF-state voltage. Because this stored energy dissipates every switching cycle, power loss is the product of stored energy and frequency: $\frac{1}{2} CV^2 f$, where $f$ is the switching frequency. Therefore, design methods that reduce power losses must reduce $C$, $V$, or $f$. Of these, reducing $V$ usually achieves the best return for the effort. The semiconductor industry proposes to reduce $V$ from its present levels of 3.3 Volts or 5 Volts to about 0.6 Volts by 2015. Smaller devices have less $C$ and the semiconductor industry proposes to further reduce device size by 2015. Unfortunately, they expect an increase in number of devices per unit area that outstrips the advantages gained by developing smaller devices with less capacitance. Operating frequency correlates directly to performance of any switching semiconductor-based system. Therefore, frequency is usually pushed as high as the chip architecture allows. Reducing voltage without reducing frequency often leads to serious performance problems that are difficult to predict, as explained later in this section. Scaling frequency with voltage mitigates and even eliminates many of these problems.

The losses described in the previous paragraph are often known as switching losses. Current flow through a semiconductor device causes another category of losses known as conduction losses. Because the semiconductor industry expects significant increases in current over the next twenty years, conduction losses will also rise. Conduction losses are proportional to $R_{d(on)}$, where $R_{d(on)}$ is the “on” resistance of the device when it conducts. $R_{d(on)}$ is expected to decrease significantly in the next twenty years, so the increase in conduction losses will be mitigated by advances in semiconductor design. As is the case with $C$, the resistance value of $R_{d(on)}$ is less in smaller devices, but the expected proliferation in number of devices per chip outstrips this advantage. Fortunately, conduction losses are usually somewhat smaller than switching losses. Therefore, most designs concentrate on reducing switching losses and will probably continue to do so.

At levels of voltage below 1.0 Volts, losses due to current leakage become comparable to switching losses. Current leakage losses are a form of conduction losses. Though semiconductor devices have a blocking state (i.e., the device can be turned OFF), they still conduct small amounts of current. The leakage current of a single device becomes quite small as rated voltage levels become less and less, but the proliferation of devices leads to significant aggregate leakage current.

Power management as an energy source

Power management can contribute greatly to the goal of 72 hours’ operation without human interface for logistics resupply. The public utilities realized long ago that conservation can be considered an energy source. They have been fairly successful in exploiting this concept, despite the fact that their tools for achieving conservation remain limited to persuasion and blackout. Persuasion has taken the form of advertising, slogans, subsidies, and legislation. The California utilities clearly demonstrated the effective use of blackout in the year 2000. These all are forms of dynamic power management.

Industry has begun to adopt an effective approach to static power management as well. Recent improvements in cell phone technology are a good example. Cell phone manufacturers recently expected that several new features might become quite popular, giving them a competitive edge. However, the combined effect of these features promised to reduce battery life by less than an hour. They developed several innovative power management techniques, as illustrated by the following examples. Researchers as the University of California reduce transmission time by designing network protocols for minimum energy consumption. Manufacturers reduce power consumption by switching into a standby mode any appropriate subsystems that such control software identifies. They design battery control circuitry that better identifies conditions that permit a standby mode. They better adapt charging circuitry to battery behavior, resulting in better energy storage efficiency. Mitsubishi combines a new low-loss integrated circuit with a power amplifier and antenna switch module, optimizing the design of the coupler and matching circuit. Other examples abound, giving cell phones substantially better energy performance now then just a year ago.

Unlike those industries described above, the Army does have a strong direct influence on the behavior of source, load, operators, and supporting logistics throughout the entire equipment life cycle. The Army also has control of
design specifications. Therefore, the Army may employ more than these industry tools to improve power management. There is also opportunity for realizing further benefits in coordinating the effort.

Techniques of power management are probably the only way to get some of the new power technologies into the inventory. An Army Science Board study confirms this for soldier systems. It is even more true for larger equipment, such as might appear in the 500 Watt to 10 kW power range. For example, TPV has significant advantages when the waste heat can be used. An example is space heaters with a small concurrent electrical output. These may not be practical for a 10kW load, but can be integrated into a system through effective power management. Once integrated, this gives the obvious benefits of diversity. The same is true for other generation technologies, such as photovoltaics.

**Expected benefit levels from power management**

Estimates of the advantage to be gained from power management range from a factor of 2 to a factor of nearly 10. A 2001 Army Science Board study of small power sources concluded the following: Improvement by a factor of 2 in soldier systems is definitely achievable within a few years. Most systems have been designed with such insufficient attention to power management that a factor of 2 improvement seems possible using technology that already exists or will be ready shortly. Predictions for improvement by a factor of nearly 10 in the long term, e.g., beyond 2015, still seem to be too ambitious for any evolutionary advancement in technology. Predictions of large improvement numbers often include aggressive power management measures that soldiers may be reluctant to adopt. At any rate, there is a great deal of advantage to be gained from power management. The Army Science Board study concludes that improvements are likely to come from a combination of organization, operation, and training.

Similar studies have been conducted for loads that would normally be supplied by power generation equipment in the 500 Watts to 10kW (and above) range. Similar conclusions appear: power savings up to 89% are possible through power management. Similar methods are proposed in these studies: a combination of organization and operation. In one group of studies, dynamic power management of modules of larger systems leads to improvements when placed in an inactive mode when not needed. Software algorithms determine when to “sleep” each module, typically after a period of inactivity. In another group of studies, innovative computing algorithms minimize software overhead and implement energy-saving ideas such as reducing the number of switching transitions needed to process typical tasks. The effect of training the soldier does not yet appear prominently in studies at this power range.

There is little doubt that significant power savings can be achieved by these methods. Continuing to fund these efforts is a good idea. Using less energy to accomplish the same tasks is a solid step toward getting 72 hours of performance from the equipment. It is evident from the studies that improvement by a factor of 2 is quite possible with the technology that is being developed. This equates to doubling the time that a generator provides power from a given load of fuel. It also means a great deal of weight and fuel savings.

**Further issues in power management**

Power management is unfortunately not as simple as merely turning equipment off when it is not needed. Several other significant issues are addressed below. These issues span power management. Nonetheless, these issues do not change the basic premise that there is a great deal to gain from effective power management.

A significant weakness that the Army Science Board study identified is the need for unity of command in designing systems that draw electric power. From a practical point of view, providing electric power is often seen as an afterthought. Tradeoffs between system performance and electric power generation are not always explicitly stated and optimized. The Army Science Board study recommends employing someone, for example, a system manager or chief engineer, specifically to integrate energy user requirements and energy provider capabilities. The Board recommends a model built on the commercial sector approach to power management: include it throughout the design and make it a part of the performance metrics. A “top-down” architecture is their recommendation: put the electric power into the design early and keep electric power among the more important aspects of a system’s design. The Board’s study addresses electric power for soldier systems, but an overview of loads in the 500 Watt to 10kW range quickly indicates that the recommendation if valid for the latter class of loads as well. Because the Army has control of source, load, designer, and user, it is reasonable to designate a fully resourced power management office
with total responsibility for power management policy and implementation. Unless this office has appropriate authority and resources, power management will likely be lost in a piecemeal fashion.

Power management includes issues of system integration. When dynamic power management is implemented, equipment performance may be unexpectedly and suddenly degraded. An interesting example is an Army audio communication device that has, among many capabilities, automatic error correction of information that it receives. The device works very well as designed. An experiment shows the device performing well as an operator begins to reduce its terminal voltage. Unfortunately, reduction in terminal voltage below a certain level leads to a sudden slowing of its output audio signal. However, there is no increase in output noise, as might be expected when terminal voltage decreases without a corresponding decrease in operating frequency. Though unknown to the user, the device had indeed been experiencing an increasing number of errors in its input signal as the terminal voltage decreased. The error correction algorithm masked them. Finally, the error correction became overwhelmed and slowed the system in order to keep pace. Because dynamic power management is likely to be applied to existing equipment, attention to possibilities such as this is necessary. At any rate, claims of significant power management improvement may be based on assumptions that unexpectedly degrade performance or may overwork subsystems that have been designed to mitigate problems. Thorough testing with an emphasis on transformation, not merely demonstration, will often mitigate problems like this.

Supplying electric power to electronic equipment will become more complex in the next twenty years and beyond. It will literally weave itself into the system blocks. It will become part of high performance systems as chip manufacturers realize a crunch for power. Power on chip will become commonplace, just as integration of memory and FPGA/DSP hybrids have become recently. Static power management will be key to making these systems practical. Dynamic power management chips are beginning to appear on the market as well.

As mentioned above, the cell phone industry engaged in a concentrated power management research effort. They took decisive steps to achieve remarkable power management, obtaining high efficiency at high current levels and managing losses. Others, including the Army, can leverage that success. Industry routinely takes the definition of power management one step further: Industry defines power management to include heat management. Effective power management leads to more moderate temperature gradients, elimination of hot spots, careful channeling of heat, and reduced transformer size. There is a multiplier effect available from heat management: Drawing less power normally means less heat generation. This requires less cooling which draws less power. Industry sometimes includes various forms of cogeneration: employing heat for useful purposes, rather than wasting it. As a survey of the power electronics literature shows, heat management remains a topic of significant concern in the research community. A number of solutions and new ideas are expected in the next few years.

Generators tend to be inefficient at light load. They require a base level of current under “no load” conditions, yielding a base level of losses as well. With increasing load, losses increase less than proportionately to the increase in load. Load balancing is a power management technique that may help: combining tasks to form larger aggregate pieces of load that can be supplied more efficiently by fewer, more heavily loaded generators. Scheduling loads together is another way to take advantage of the better efficiencies available from loading a generator more heavily. The operations tempo may not always encourage load balancing, but it is a useful tool in many cases.

Some power management proposals may not always reflect the soldier’s view of the world. A study of dynamic power management shows some unrealistic proposals on occasion. Power management means turning things off when not needed, but the “when not needed” must be carefully defined. Soldiers need performance and ease of navigation. Soldiers need tools that are immediately available at full capability on demand. In light of this, zeal must be tempered and power management must be held to a high standard when rules and hardware are being designed: Emphasize transition rather than demonstration; fielding rather than prototype; Include fault tolerance in every dynamic power management method. In short, as the Army Science Board study concludes, be realistic and cautious when employing power management.

The goal of 72 hours of tactical mobile electric power without logistics resupply is indeed a difficult one. Without effective power management, that goal will recede beyond the horizon. The Semiconductor Industry Association’s (SIA) latest roadmap shows operating voltage for mobile systems decreasing by a factor of 5 to 0.3V by 2014. Operating frequency rises by a factor of 11 to 13.5 GHz. As a result, power consumption nearly doubles. Without
power management, this consumption figure would be much worse. In other words, power management may bring the not merely significant power savings, but will keep a difficult situation from getting completely out of hand.

Conclusions
Power management is defined as minimizing power consumption by using power only when necessary and then only in the most efficient manner. Power management holds great promise for reducing electric power demand. Without it, the growth in power demands may drive the goal of 72 hours completely beyond reach. Through power management, new power technologies can become practical pieces in an integrated system.

Power management may be characterized in two categories: dynamic (making decisions to reduce energy consumption in real time) and static (designing a system with energy conservation in mind). In static power management, industries such as cell phones and automobiles have begun to fund research at significant levels and have made important contributions that the Army can leverage.

Like other energy technologies, power management has its share of hype and rosy scenarios. A factor of 2 improvement appears to be quite realistic fairly soon. A factor of 10 improvement is probably not. Because design practices, as well as tactics, techniques, and procedures, are not yet optimized for power management, improvements gained by employing it may initially be quite significant. The keys to success are twofold: including energy conservation early when designing equipment, defining and optimizing it against other performance measures, and taking real time measures to conserve energy, such as software enhancements and training the warfighters to work with their equipment to save energy wherever possible.

Hybrid electric vehicles
A Hybrid Electric Vehicle (HEV) uses a combination of an automotive engine and electric motor drive system. The former provides baseline power and the latter provides peaking power and acceleration. The automotive engine can be based on almost any of the power technologies under consideration in this report. This engine typically has a capacity of 10kW to 50kW in most commercial models. Military HEVs have been proposed with engines from approximately 30kW to 300kW. Within five years, the automobile companies plan to introduce hybrid electric vehicles (HEV) into the market. For example, Toyota has set a goal of producing 300,000 HEVs annually by 2005. If the HEV becomes successful, there are important implications for tactical mobile electric power.

Research issues
The primary technological issues facing HEVs are managing multiple energy sources, battery sizing, and battery management. For practical purposes, all three of these issues should be resolved well before 2015. The Uninterruptible Power Supply industry has addressed the first issue already. Those involved in distributed power are quickly following suit. HEVs have an advantage in battery sizing and battery management (compared to the all-electric vehicle) because the automotive engine biases the energy requirement quite favorably. HEV prototypes have been publicly shown already with battery banks that fit the vehicle appropriately. Significant levels of production are proposed for the 2005-2007 time frame. Despite a rather bright technological picture, it remains to be seen whether customers will find an HEV attractive. If they do, then having a significant number of HEVs on the road will help leverage the technology.

If the electrical portion of a HEV could be designed to supply an external load such as a shelter full of electronics, then a trailer-mounted design for tactical mobile electric power may become unnecessary in some cases. The approach that is most often proposed is to add an inverter between the HEV’s dc link and the load, converting the HEV’s dc (from its battery or generator) into ac for a conventional interface to the load. The inverter can have any power rating up to the power rating of the automotive engine. Unfortunately, that inverter is the major obstacle to using HEV technology for mobile electric power. The reasons are its weight, heat, and noise. Another possibility is to supply the load with dc. The issues involved in doing this are discussed later in this report. In either instance, a trailer-mounted generator design becomes unnecessary, at least for average power generation levels near the power rating of the HEV’s automotive engine. The electrical portion of the HEV adds a pulsed load capability and a limited capacity for a silent mode. Because energy storage proposed for the HEV will be greater than the energy storage in legacy equipment, the HEV’s silent mode will be somewhat greater.

An HEV’s traction motors are likely to be an ac machines. In that case, using the HEV’s traction motor drives may seem to be a possible alternative to obtain ac for the load. However, this is impractical for a number of reasons. For example,
these motor drives are optimized for traction and not for interface to an electronic load. Also, because the operating frequency of the traction motor and the electronic load are rarely the same, one motor drive cannot take both at the same time. Operating the electronics while on the move will not be possible.

When using the HEV for tactical mobile electric power generation, power management will be important. Many missions require less than 10kW, but have a HEV of 30kW or more supporting the mission. The HEV’s energy storage allows light load to be addressed by on-off cycling of the automotive engine, a form of power management. In this case, the engine will definitely cycle far less often than legacy equipment does. Methods of light load mitigation, discussed within respective power technology sections of this report, can also help address this problem. At the heavy end of the load continuum, capacity may become a problem if the electronic load is operated while the vehicle has a heavy propulsion load. However, the technology to manage such a situation is the same as the technology required to perform battery management.

Conclusions
Hybrid Electric Vehicles will probably become ubiquitous several years before 2015. By definition, each HEV contains a vehicle-mounted electric power generating system. Through an inverter, this power can be made available to an ac load. The amount of power generated by the expected military HEVs can eliminate the need for a trailer-mounted generator in the 500 Watt to 10kW (and more) range. Energy storage aboard the HEV provides the possibility of a silent operation capability. The difference in power ratings between HEV and load will require dynamic power management.

Power Quality and UPS Technologies
Power quality has become an important issue in industry and will become likewise important in tactical mobile electric power generation. Power quality is defined as the effectiveness of the interaction between electrical power and the electrical equipment that it runs. If the equipment operates properly, then the power is of good or acceptable quality. If the equipment fails to operate properly or is even damaged because the power does not behave as expected, then the power quality is said to be poor. Power quality equates to voltage quality in most circumstances. The ideal voltage waveform is either sinusoidal, in the case of ac, or a fixed constant value, in the case of dc. Deviations indicate some degree of imperfect power quality. When the deviations cause the load to fail to operate properly, there is said to be a power quality problem. This is a serious issue because poor power quality causes significant loss of production in a wide range of industries.

UPS technologies and tactical mobile electric power design
Power quality issues are of several kinds, classed by their nature and duration: voltage transients, voltage and current harmonics, voltage swells and sags, and voltage interruptions. On-line UPS systems mitigate each of these kinds of power quality problems to some degree. An on-line UPS system is one that operates continuously, rectifying the incoming voltage to dc and then inverting that dc to a fixed frequency, fixed voltage amplitude output voltage to a load. The dc also charges an energy storage device, usually a battery. If the incoming voltage is interrupted, for example, energy storage supports the load for a period of time. This period of time is designed to be long enough to take other measures, such as starting an emergency generator or shutting down the load in an orderly fashion.

The topology of the AMMPS power converter is quite similar to an on-line UPS: a generator or source whose voltage and frequency are not constant, a dc link with some energy storage, and an inverter that produces a fixed frequency, fixed voltage amplitude output. The major differences are 1) AMMPS stores a much smaller amount of energy on the dc link, 2) AMMPS has a widely variable input frequency capability, and 3) AMMPS ordinarily does not have as wide or as rapid variations in voltage. Given the great similarities, UPS design ideas may enhance mobile electric power generation.

Examples of power quality enhancements
Out of tolerance detection. UPS companies have sophisticated methods of determining whether a voltage or current waveform is within tolerance. These include digital signal processing methods that take a number of variables into account, such as depth and duration of amplitude deviation, frequency deviation, spectral content, etc. Several corrective actions are available, such as boosting the dc link voltage, transferring to energy storage, switching to an alternate source, etc. In a similar manner, digital signal processing methods can also determine when the source has returned within tolerance and then resume normal operation.
Ride through: This concept normally relates to the ability of a load to endure sags or interruptions without adverse effects. The Information Technology Industry Council (ITIC) publishes a recommended standard for electronic equipment tolerance to voltage sags and swells. Known as the ITIC curve, it specifies a minimum acceptable ride through for electronic loads. There are several curves of this nature, but this is the most well known and accepted. Military loads may often have different purposes and sensitivities than commercial loads. However, a fairly rugged standard for sensitivity of loads should be maintained and regularly coordinated with specifications for mobile electric power.

In the case of mobile electric power, an AMMPS topology gives the opportunity to add energy storage to the dc link. The amount and type of storage strongly affects ride through. It may also influence inrush current at startup. The obvious tradeoff is in weight and expense of extra energy storage for duration of ride through.

Transient abatement: Transients are short aperiodic variations, typically having a frequency more than ten times greater than the fundamental frequency. Often, they are called surges or spikes. Any power electronics should have protection against them. Fast, inexpensive devices now exist to suppress transients. These are expected to improve significantly in the next twenty years, particularly in the amount of energy that they can absorb for a given physical size.

Harmonic reduction: Harmonics are periodic deviations in the voltage or current waveform. Harmonics, by definition, have frequencies that are integer multiples of the waveform’s fundamental frequency. A benefit of an on-line UPS is that harmonics rarely pass through. Unfortunately, the inverter stage of a UPS can generate its own set of harmonics. Excessive values of certain harmonics, such as zero sequence harmonics or a rectifier’s typical odd sequence current harmonics, can stress and even damage equipment. The key to employing harmonic reduction is to understand how the load responds to the amplitudes and frequencies of the harmonics that it is given: If the load performs within specifications, then harmonics are not a problem.

Fast transfer switch: A power quality technology that has become successful in recent years is the fast transfer switch. This is a thyristor-based switch that can transfer a load from one generating or distribution source to another in less than one-fourth of a 60 Hertz cycle. UPS manufacturers have somewhat faster transfer switches. Recent research efforts have been concentrating on increasing the upper voltage limit; however, existing technology already more than adequately covers today’s mobile electric power equipment and any future requirement that is likely to appear. In combination with load equipment that meets even minimum ITIC standards, a fast transfer switch provides the reliability promised by a backup energy source without power quality problems. Obviously, a fast transfer switch requires a backup generator, a situation that does not always exist for tactical mobile electric power.

Conclusions
Just as power quality has become an important issue in industry, it will also become important in tactical mobile electric power generation. Power quality problems such as voltage transients, voltage and current harmonics, voltage swells and sags, and voltage interruptions may adversely affect system performance. Tactical mobile electric power will face these problems to an increasing degree in the next twenty years. Fortunately, the technology to address these issues does exist, such as methods for out-of-tolerance voltage detection and mitigation, ride through, harmonic reduction, surge suppression, and fast transfer methods. This technology will continue to develop in the power quality industry, in such places as the UPS companies, the power supply companies, and those who manufacture surge suppressors, power line filters, and other power quality mitigation equipment. Clear power quality standards for electronic load equipment must be regularly coordinated and enforced. Designs for tactical mobile electric power must include appropriate attention to power quality, for example, in designing appropriate energy storage and in specifying appropriate equipment to prevent or mitigate power quality problems.

Fuels
The fuel standardization policy from DoDD 4140.25 reads as follows:

Combatant Commanders shall develop plans to minimize the types of fuels required in joint operations. …Primary fuel support for land-based air and ground forces in all theaters (overseas and CONUS) shall be accomplished using a single kerosene-based fuel, in order of precedence: JP-8, commercial jet fuel (with additive package), or commercial jet fuel (without additives), as approved by the Combatant Commander. Fuel support for ground forces may also be accomplished using commercially-available diesel fuel when supplying jet fuel is not practicable or cost effective. …To the maximum extent practical, no new combat
support or combat service support equipment or vehicles requiring gasoline-type fuels will be acquired or developed unless the support concept is to supply fuel as a packaged product.

Of the possible energy technologies that might be appropriate for mobile electric power, the following normally use fuels compatible with this policy: internal combustion engine, turbine, thermophotovoltaic, and external combustion. The high energy content in tactical fuels leads to effective performance. The following do not use these fuels: radioisotope (carries its own nuclear fuel) and energy harvesting methods (capture ambient energy). The fuel cell is the most attractive technology at hand that is rendered significantly less attractive by this policy.

Possible fuels mentioned for fuel cells are hydrogen, alcohols such as methanol, gasoline, and diesel. Hydrogen distribution systems have not been developed. Industry appears unlikely to make the investment to do so while gasoline remains dominant as a motor fuel. The latter three fuels require reforming into hydrogen. Methanol is likely to become the fuel of choice for fuel cells in Europe, but most American companies view using it as an intermediate step in fuel cell development. Efforts to build a practical gasoline reformer have not yet been successful, though there are recent claims to the contrary by General Motors. At any rate, the fuel policy eliminates gasoline as an option. No practical diesel reformer currently exists or is likely in the foreseeable future. The military is the only large customer that wants a diesel reformer. Because the military market is small by comparison, it is unlikely that industry will commit the large investment to develop such a reformer. To make matters worse, sulfur in concentrations exceeding 0.1 part per million poisons the chemical reaction underlying PEM fuel cells. Unfortunately, sulfur is a common component of logistic fuels in many possible host nations. Removing sulfur requires specialized equipment, increasing overall system size and weight. Therefore, a practical fuel cell that uses logistic fuels appears unlikely in the next twenty years.

Alternative fuels such as hydrogen and alcohols are proposed for other generation technologies also. However, alternative fuels have neither the market nor a system for large scale production, distribution, and storage. The cost of building such a system and the cost of the fuel itself are both high enough to discourage investment at present. In fact, building such a system may cost substantially more than the total cost of making the fuel cell itself into a commercial product. Gasoline, diesel fuel, and jet fuel are cheap and plentiful. The transportation industry gives them a huge market and great economies of scale. An effective production, distribution, and storage system already exists. The proven reserves will last beyond 2025. Advances in engine technology may encourage some fuel combinations, such as gasoline-ethanol. Even then, the hydrocarbon component will continue to be dominant. Therefore, it is unlikely that hydrocarbon fuels will be displaced by alternative fuels in the next twenty years.

**Electric machine**

Professor Thomas Lipo, probably the world’s foremost expert on electric machines, was asked which electric machine would be best for the medium sized military generator in 15-25 years. He replied without hesitation that a permanent magnet (PM) machine would be dominant in this power range. PM machines have a great deal to recommend them: self exciting, compact, low losses (compared to other machines), and quite rugged. Their problems concern field weakening, dealing with faults (internal and demagnetizing), and appropriate converter topology. The electric machine in AMMPS is a PM machine.

**Machine options**

Other machines include wound-field synchronous, reluctance, and induction machines. Compared to a PM machine, these are all less compact and less efficient. Exciting them is more complicated. All have a reputation for acceptable ruggedness; reluctance and induction machines are known to be more rugged than PM machines. The wound field synchronous machine has an advantage over all other machine types in field control, to include field weakening. Issues relating to converter topology are similar for all machines.

In the wind turbine industry, the most commonly installed generator is now the doubly fed induction generator with a back-to-back voltage source converter that feeds the rotor winding. Wound field synchronous generators are increasing their share of the market. The squirrel cage induction machine is losing market share. The doubly fed induction machine has the advantages of variable speed operation, field control, and low harmonic content in its output. It is not self-exciting, it has a wound field, and its power electronics are of similar complexity to those
typically driving a PM machine. The wind turbine converts variable voltage, variable frequency (VVVF) ac to fixed voltage, fixed frequency (FVFF) ac using a variable speed generator, a task that is somewhat similar to tactical mobile electric power.

The PM machine’s significant disadvantage among these machines remains the difficulty of controlling, particularly weakening, the field and its weak ability to deal with faults. By 2015, the field weakening problem of PM machines should be solved. Significant progress has been made on this problem in the past few years. Advances in processor technology will permit tighter and tighter control of excitation, torque, and speed. Several solutions now being developed appear promising in simulation. These should appear in the literature within 3-5 years and will be in production before the time period in question.

Mitigation of faults will remain a problem. PM machines exhibit more than the same underlying sensitivities to overcurrent that other machines have. Unfortunately, many faults that have minimal effect on other machines can demagnetize the PM machine’s permanent magnets. Advanced generator fault detection techniques exist, but are too costly to install in the 500-Watt to 10kW power range. Most of the research in advanced machine fault detection, suppression, and protection is for larger machines, such as those found in the public utilities and in heavy manufacturing. It will probably take more than twenty years before the results of this research can be economically leveraged into the power range in question. The Navy expects to have such technology on its smallest shipboard power systems no earlier than about 2035.

Manufacturers favor a radial air gap in this machine size range. They tend to be less sensitive to thermal expansion that axial air gaps. Fabrication is easier because a better manufacturing base exists worldwide to do so.

PM machines have finally grown into medium power generation. As the remaining issues are addressed as described above, they will dominate this power range for the foreseeable future. It is likely that their remaining problems, except fault mitigation, will be resolved by 2015.

Variable speed operation
Variable speed operation strongly enhances the operating characteristics of rotating generator systems. A power electronic converter is the most effective means to obtain FVFF ac power from a variable speed generator. The technology of electronic power converters has advanced tremendously in the past twenty years with the advent of fast switching power semiconductor devices that able to handle megawatt loads. As a result, ratings for voltage, current, and switching time of devices are now more than sufficient for any tactical mobile electric power generator that the military is likely to require. The primary limitation of switching devices will continue to be thermal dissipation capacity, a characteristic manifested primarily as a limit on switching frequency. This has been the limitation of power semiconductor devices for four decades and will continue to be the case for the foreseeable future. A high switching frequency enables the use of the sophisticated control methods that underlie a number of improvements in performance. For the electrical side, this includes improved waveshaping to reduce harmonics, faster response to controller commands and power quality problems, and elimination of audible noise. On the prime mover side, better optimization of speed and torque leads to improved emissions, better efficiency, and reduction of light load effects, such as wet stacking. In the next fifteen years, switching speed may not improve nearly a thousandfold, as it has in the past fifteen years, but nanosecond switching at voltages and currents throughout the military’s mobile electric power inventory should become the order of the day. This will place a premium on low-inductance circuit designs, further encouraging compactness. For example, Professor Lipo has several machines in the laboratory that dramatically improve the inductance distribution of these machines and the power converters that drive them. These will appear in the literature in the next few years and in the inventory by 2015.

Vector Control
Vector control strongly enhances the flexibility of variable speed generators. Machines with vector control can follow loads precisely, responding in a few milliseconds to torque steps as great as the machine’s full rating. Vector control has become practical due to strong advances in microprocessor speed and power. For generators, much of this technology has appeared first in the wind turbine industry. Advanced control designs, such as vector control, have strongly improved system response, stability, and reliability. As shown in the IEEE Power Engineering Society Winter Meeting in 2002, these developments have begun to appear on medium sized generators. Because the Europeans are now leading the progress in the wind industry, many of the new developments will come from
them. Vector control will be commonplace in high performance generating systems long before 2015.

Other advanced control methods are also appearing in electric machine drives. These include various methods of advanced pulse width modulation, fuzzy logic, and neural network methods. Some of these are discussed in the next section of this report.

Information technology will further improve the performance of electric machines. For example, an American manufacturer has a prototype 2kW PM generator with an inverter that switches above 20kHz. Its electrical system efficiency exceeds 90%. The drive system is run by advanced digital signal processors linked to a central controller by a CANbus architecture. Wireless control is soon to come.

**Conclusions**

The PM generator is now the machine of choice for tactical mobile electric power. PM machines have a great deal to recommend them: self exciting, compact, low losses (compared to other machines), and quite rugged. The electric machine in AMMPS is a PM machine. A few issues remain to be resolved such as field weakening, fault performance, and appropriate converter topology. These should be resolved by 2015, though fault performance may be an exception. Advanced control methods that were developed for motor drives on wind turbines are now being applied to PM generators. These will be available commercially before 2015.

**Power electronic converters**

Advantages of variable speed generation are introduced in the electric machines section of this report. Power electronic converters provide a means of converting VVVF ac power to FVFF ac to gain these advantages. In the most common power electronic systems, Pulse Width Modulation (PWM) of the output voltage provides the desired output currents to drive the load. There are a number of power electronic converter circuit topologies that can provide those voltages. In this subsection, those power electronic converters are discussed.

Switch-mode converters have dominated the industry since the 1970s, being far more energy efficient than their linear cousins. In fact, linear converters are typically used only where switching noise is a problem. Most ac loads above 500 Watts have a three-phase topology, so the converter is three phase as well. A three phase topology has dominated the industry worldwide for more than three decades and will continue to do so. For example, modularized power converters, such as the Navy’s Power Electronics Building Blocks (PEBB) and ST Corporation’s modular power converters, are based on this structure. Most of the advanced control methods, both established and experimental, generally assume the standard three-legged architecture. Though many have proposed more or fewer phases for a host of reasons, a three phase design framework remains dominant everywhere. This shows no signs of changing.

**Power Converter Topologies**

For a medium sized mobile electric power generating system, there are several possibilities for power electronic converter topology itself: multilevel, cycloconverter, resonant, matrix, and dc link. The multilevel topology has advantages primarily for very large power converters, such as those found in electric utilities. The seminal advantage of a multilevel topology is that it allows the circuit designer to use large, slow-speed semiconductor devices to create output voltages that are low in harmonic content. At very high voltages, these are the only devices available. In medium sized mobile electric power generation, individual fast switching devices are quite capable of handling any possible voltages and currents. For the power levels at hand, there is little advantage to be gained from a greater number of switching devices and the complicated switching algorithms of a multilevel converter. The same is true for a cycloconverter for essentially the same reason.

Resonant converters seemed to proliferate in the research literature in the past decade or so. Their most important advantage is the fact that they have negligible switching losses. This allows them to switch somewhat faster than other converters, producing more accurate output waveforms while generating fewer switching losses and less harmonics and EMI. Unfortunately, their larger energy storage elements and greater complexity makes them less competitive except where extremely fast, accurate voltage or current response is important. Resonant converters still have few commercial applications. In fact, only one company, Soft Switching Technologies of Madison, Wisconsin, has ever produced a commercially competitive resonant converter in quantity. Because power
semiconductor devices have become more than ten thousand times faster than they were less than a decade ago, the resonant converter has a lot of its waveshaping and efficiency advantages over other topologies. As a result, resonant converters are still not competitive for tactical mobile electric power and will likely remain so.

Matrix converters are ac to ac converters, able to handle VVVF ac on both input and output. In one direction, they have a boost capability. Within device limits, they have a universal input voltage capability. They are fast enough, like the resonant converter, to influence power quality. Their output does require filtering, but inductive loads take care of that by their nature. In addition to advantages in waveshaping, matrix converters do not need the large capacitor that occupies the majority of the physical volume of dc link and multilevel converters.

Matrix converters have been studied for several decades. Until the past few years, they were considered to be impractical because the computation burden was too great. Also, power semiconductor devices switched too slowly to enable accurate waveshaping and digital signal processing was too slow to make real time control possible. Fortunately, devices and signal processors have finally become fast enough to change this situation. Matrix converters and degenerate cases of them now appear in the technical literature and even in some commercial products.

For medium sized mobile electric power generation, the matrix converter’s advantages come with some significant tradeoffs. First, without the energy stored in a dc link capacitor or battery, a matrix converter has little “ride-through” during disturbances. For an electronic load that may be fairly sensitive to disturbances and in light of the expected tactical environment, this is a serious problem. Second, very fast “hard” switching of the semiconductor devices, as is typical of matrix converters, generates significant amounts of EMI. To make matters worse, matrix converters have exacting switching algorithms that often are susceptible to noise. In other words, matrix converters tend to foul their own electromagnetic environment and then complain about it. Third, a true matrix converter has nine bi-directional switches, more than the six unidirectional switches of a dc link converter. Fortunately, Johann Kohler has pioneered some reduced-device matrix topologies, saving money and complexity. The reduced topologies operate in only one direction, but that is not a problem in this case.

As active power management becomes more common, imbalance among phases may appear. Four-legged architectures give a greater degree of flexibility, having a natural half-power point and tolerating imbalance much better. They are also more fault tolerant. Each of the converter topologies discussed above has its own four-legged form. The issues, good and bad, are the same. The downside of a four-legged topology is that it requires proportionately more switching devices.

The dominance and practicality of the dc link converter will keep it popular beyond the foreseeable future. Other topologies have niches. However, for economy, flexibility, simplicity, ride-through, and ruggedness at the voltage, current, power, and frequency range appropriate for medium sized mobile electric power conversion, none of the other converters appears competitive.

Other Issues
It is possible to provide electric power simultaneously to several loads at multiple frequency and voltage levels. In the past, this required at least one generator for each load that had a unique frequency and voltage combination. Power electronic converters can supply these diverse loads from a single generator. The power electronic converter needs only one rectifier section, but it does require a unique inverter section for each unique simultaneous load frequency and voltage combination. For example, a single generator with one rectifier and three parallel inverter sections can provide an output at 230V, 60 Hz, another output at 120V, 400 Hz, and a dc output as well. Assuming the semiconductor devices can handle the voltage, current, and switching frequency, it is merely a software modification (perhaps entered from a computer terminal remotely) to modify voltage and frequency.

A variable speed capability also permits a tighter control of frequency and voltage. This gives an immunity to variations in frequency or voltage arising from imperfect operation of the prime mover. Combined with advanced signal processing in small, inexpensive packages, this can bring the advantages to networking generators to somewhat lower power levels than were previously possible.
A great deal has been said about Silicon Carbide switching devices. Their speed, forward voltage, and efficiency are a significant improvement over today’s switching devices. However, there are a number of problems to be overcome before silicon carbide devices become practical. Like fuel cells, they have been within a few years of commercial reality for a long, long time. Therefore, it is difficult to determine whether they will be available by 2015 or even 2025. If they are available, then a new generation of faster, cooler designs will appear quickly. It is more likely that they will not be available by then.

An excellent source of the latest and most innovative power electronic converter technology is found in the Uninterruptible Power Supply (UPS) industry. As mentioned earlier, an on-line UPS uses essentially the same dc link power converter circuit as a variable speed generator. The UPS industry has been selling power converters for several years in the power range in question. They include such features as waveshaping, detecting when the source has varied or disappeared, static transfer, battery charging, on-line and off-line UPS technology, etc. They have already interfaced to microturbines, fuel cells, wind turbines, photovoltaics, and the utility grid. Likewise, the power supply industry makes products for the communications and industrial markets such as dc/dc converters, inverters, frequency converters, variable speed motor drives, and static transfer switches. The Navy has developed modular approaches to power conversion in general, as have several power supply companies. The technologies that these companies will sell are the underlying technologies that will dominate power electronic conversion for medium sized, mobile electric power for the next twenty years and more.

Conclusions
Several power converter topologies appear to be appropriate for medium sized power conversion: multilevel, cycloconverter, resonant, matrix, and dc link. For economy, flexibility, simplicity, and ruggedness at the voltage, current, power, and frequency range appropriate for medium sized mobile electric power conversion, the dc link converter appears to be the most appropriate for the foreseeable future. Matrix converters are gaining some popularity, but their lack of “ride-through” is a problem. Companies in the UPS industry and the power supply industry, as well as the Navy, have developed power converter technology for applications that are remarkably similar to the VVVF ac input to FVFF ac output that will be required of a tactical mobile electric power generator.

DC Microgrid Technologies
Is ac or dc better for this application? This issue is not new. Precisely a century ago, the same question was the most hotly debated topic in the public utility industry. By 1910, ac won the debate due to superior transmission and distribution efficiency provided by the transformer and the less expensive ac switchgear. However, tactical mobile electric power has no long transmission or distribution lines and needs no large transformers. And 1910 was long before power electronics existed.

In the AMMPS topology, a generator produces ac variable voltage amplitude, variable frequency (VVVF). This ac is then rectified to high voltage dc. That high voltage dc is then inverted back to ac, though fixed voltage amplitude, fixed frequency (FVFF). This FVFF ac is the input to an electronic load that immediately rectifies the ac back to high voltage dc. Most electronic loads have further power conversion steps, but those are beyond the scope of this discussion. The point is that two of these steps may be unnecessary if dc does the power distribution. The perhaps unnecessary steps are inverting high voltage dc to ac FVFF and rectifying that ac back to dc.

Advantages
Most existing electronic equipment that draws FVFF ac power immediately converts that ac to dc for use in the electronics. Only an occasional indicator lamp or fan uses FVFF ac directly and even that is becoming rare. As a result, dc is actually how power is supplied internally to most commercial off-the-shelf electronic loads.

The obvious benefit of using dc distribution is a savings on equipment: There would be no need for these two power converters in providing tactical mobile electric power. The savings is significant in cost, weight, volume, maintenance, and reliability. A rule of thumb is that power electronic converters cost as much as the electric machine in a given generation system. They can weigh from 40 kg to 300 kg, depending on whether they process 500 Watts or 100kW, respectively. They occupy precious space and generate heat. Though they can be built to be quite reliable, the combat system that they support will fail if they ever should fail.
A further benefit of using dc is the reduction in electromagnetic interference (EMI). The magnitude of harmonic currents and voltages that enter the distribution system are somewhat smaller for dc distribution than for ac distribution and they are easier to filter.

Disadvantages
With these advantages, why use ac? The following objections are raised:

- **Host nation support:** Host nations usually distribute ac FVFF. Therefore, loads should have an ac FVFF interface to be compatible with such power sources. Consequently, mobile electric power should also have an ac FVFF interface to be compatible with the same loads. With the advent of universal voltage interfaces, this objection may be no longer as valid. Universal input voltage interfaces provide the load with an ability to accept ac at a wide range of voltage level. It is possible to modify the interface to accept dc. Universal input voltage technology is just beginning to appear in top-of-the-line small appliances. By 2015, it will be commonplace among manufacturers who sell appliances in several nations.

- **Circuit protection:** Protection of the generator and the load is more difficult and expensive when high voltage dc must be interrupted. It is far cheaper and easier to interrupt high voltage ac. Therefore, in power conversion systems having both ac and dc sections, there is a strong preference for doing the circuit protection in the ac sections.

- **Legacy equipment:** Legacy electronic equipment requires ac input. If generation is dc, then legacy equipment is incompatible or would require an inverter. However, for 2015-2025, there may be time to transition to designs that can accept dc input.

- **ac is needed for a host of small platform tasks:** Little fans and motors work better on ac. The automobile industry recognizes this and has many small inverters throughout their vehicles. These are tiny and lightweight. It is cheaper to use small inverters for these occasions than to use a big one on all the power. Ironically, this objection is actually an argument for dc, now that power electronic inverters in automobiles are so cheap and reliable for such purposes. The exception is environmental control, i.e., air conditioning. Legacy environmental control units use motors that run on FVFF directly. In the IBCT Brigade TOC, air conditioning comprises more than a third of the load. In that case, distributing both ac and dc in the same shelter gets expensive. However, variable speed air conditioners, such as those that are popular in Japan, are somewhat more efficient than their ac counterparts. A quick look inside reveals that such variable speed cooling units have a dc link topology, a fact that makes a dc input all the more attractive in the first place.

**dc Microgrid**
The Navy will modify its power distribution concepts for ships entering the inventory in 2030 and later. These ships will have ac for generation and transmission, but have dc microgrids within various sections of the ship. Each dc microgrid will be connected to the ac distribution and generation system through two ac / dc converters. The advantages to this are fivefold:

- dc power goes directly to digital devices without a separate rectifier for each piece of equipment.
- Increased reliability by reducing the spread of disturbances.
- Each dc microgrid section has its own independent interface to the ac distribution system, including energy storage for enhanced ride-through. The decreasing cost of power electronics makes this affordable.
- dc cables can be run in the same paths as signal cables and other utilities. dc cables need less insulation.
- By 2005, the public utilities will begin implementing dc microgrids. The Navy leverages that technology.

dc microgrid technology tends to be something considered for higher voltage systems, e.g., 480V to 13.8kV. However, advances in microprocessor technology for interfacing and control may make such an idea eventually feasible for smaller systems. There is an advantage for reliability and EMI reduction in doing dc shelter by shelter or perhaps in groups of shelters in higher headquarters, but with ac as the main generation and host nation support. As mentioned above, the Navy does not expect this technology to be available at 480V until near the year 2030.

**Conclusions**
Power electronics have reopened the question of whether to distribute dc or ac in the power range common to tactical mobile electric power. Using dc yields significant savings in equipment costs because electronic loads are internally dc in nature. However, compatibility with host nation support favors the continued use of ac. Legacy equipment, particularly single speed, direct drive air conditioning, complicates any transition from the present FVFF.
ac to dc. There is an advantage for reliability and EMI reduction to be gained by using a dc microgrid concept shelter by shelter, complete with energy storage for ride-through. Unfortunately, dc microgrid technology at the voltage levels that the Army uses will probably not be available until the year 2030.

Circuit Protection
For tactical mobile electric power rated at 10kW or less, circuit protection has consisted of a simple breaker based on a fixed time-overcurrent trip characteristic. Maximum interruption ratings for such breakers are typically 10kA. Their I²t value is typically quite large, rendering them slow and inadequate to protect many pieces of electronic equipment. Fortunately, advances in circuit protection provided by fast digital signal processing and small, inexpensive sensors, will bring important new capabilities to tactical mobile electric power distribution.

Programmable breakers have been available for more than a decade. Their time-overcurrent characteristic can be programmed to better serve a desired load. For example, a small I²t value can be programmed when protecting loads having semiconductor devices. Their characteristics can be coordinated with other breakers in the system. Unfortunately, they are now too expensive for use at 10kW and below. With advances in embedded processor technology, the cost of these breakers has been steadily decreasing. Something of this nature may become accessible for generators in the 500 Watt to 10 kW range in 20 years.

Relaying for circuit protection has the reputation of being something that only the public utilities and their largest customers can afford. In recent years, digital relays have replaced much of the expensive traditional hardware. Digital relays have the full range of protection capabilities, all of them easily programmed and adjusted from a laptop computer: time overcurrent, instantaneous overcurrent, directional, ground fault, negative and zero sequence detection, undervoltage, overvoltage, underfrequency, overfrequency, and reclosing. They also have advanced communication capabilities, metering and event reporting, self-testing, fault-locating information, programmable logic and analysis, and multiple setting group features. Those designed for generator protection have a full range of generator fault analysis and protection tools.

Digital relays have begun to appear even in distribution systems (4160V – 69kV) because they are less expensive than traditional equipment. This is still a great deal beyond tactical mobile electric power, but the capabilities are attractive. In twenty years, some of the largest mobile electric power units may have many of these features in their protection design. Some of the smaller generators may even have a few of these features to enhance the generators’ reliability. Even if these features remain beyond tactical mobile electric power, tactical mobile electric power can benefit by leveraging their communications methods and integrated protection algorithms when networked.

Server Load
The electric utility industry is finding that electronic server load is growing dramatically. For example, estimates in metropolitan Seattle are for servers to comprise as much as 20% of the entire electrical load as Internet coverage expands in the next 10 – 15 years. Entirely new substations are being built specifically for “server farms”.

As the Army goes to greater and greater use of information technologies, many of them server-based, this part of the electrical load will expand significantly. How these servers will be placed is yet unclear. It is likely that some of the server load will be collocated with the respective operational and logistics elements. In that case, electronic load and cooling requirements would increase at those places. There is a significant reserve electric power capacity that should be able to handle this load. For example, in an IBCT Brigade TOC, more than 53% (92.1kW of the rated 173.2kW) of mobile electric power capacity is unused when all equipment is operating as designed. Depending on how large this server load becomes, equipment designers may become inclined to specify either larger mobile electric power units or more of them.

It is also likely that dedicated server shelters will be needed at points where the flow of information converges. In many cases, these may have their own dedicated mobile electric power units; in other cases, they may be part of a larger power system. At any rate, the number of tactical mobile electric power units will increase and perhaps the average size as well.
Other Performance Enhancements
The list of performance enhancements can seem to be endless. Those discussed above and in Section VI are among the more significant. There are also a few others that merit at least a listing, though there is insufficient time and space to do more. A few general comments on these are given below.

Materials
This is actually a very significant performance enhancement. In this report, it is addressed with the respective individual technologies. For example, in the internal combustion engine, advanced composite materials will be at the heart of a large share of the technological progress in the next twenty years and more. New materials will channel heat efficiently, reduce lubrication requirements, provide more optimal fuel burns, enable more effective sensing and control, etc. In fuel cells, new materials will lead to better reformers. In PV, TPV, and thermoelectrics, new materials may bring efficiencies up, perhaps to competitive levels. In batteries, advances in lithium technology will reduce weight and improve power density. New materials will make flywheels safer, smaller, and more energy dense. In semiconductor devices, silicon carbide may finally become practical. Acoustic noise abatement technology has contributed a great deal to the Tactical Quiet Generator (TQG). Further progress will reduce the acoustic signature of internal combustion engines by a few more dB or more by 2015. There are a host of other enhancements based on better materials, several of which are addressed in this report with their respective technologies.

Lubricants and lubricant free technology
There has been a series of significant advances in friction abatement materials in the past few years. Lubricant-free operation is already here for turbines and high speed electric machines. Use of lubricants in internal combustion machines will be significantly less by 2015, though true lubricant-free operation is likely to still be several years beyond that. Nonetheless, even a partial reduction in the amount of lubricants gets multiplied favorably across large numbers of units.

Simulation
The benefits of simulation for tactical mobile electric power can be grouped into two broad categories: design and training. For design, simulation tools have made tremendous advances in the past decade. General engineering simulation programs, such as ACSL and MATLAB / Simulink provide platforms for a wide range of design tasks. Specialized software has also been developed for a great host of tasks, such as all facets of automotive design, turbine design, heat transfer, electromagnetic design, chemical processes, semiconductor device design, power flow control, ergonomics, and a host of other equipment and processes. In many cases, these design tools have become PC-based because the PC is now more capable than supercomputers were a decade ago. Graphical user interfaces have become the order of the day, a strong improvement over the tedious text-based interfaces that were ubiquitous less than ten years ago. With some software packages, when a design is complete, advanced design tools actually enable a design or modification to be downloaded directly into production. For example, nearly all circuit boards are fabricated that way. For the future, these tools will become more capable, particularly in their graphical interfaces. The capability to interconnect various design simulation tools will also improve significantly. In fact, interfacing several pieces of software into a coherent and useful system will replace programming as a basic computer skill for entry-level engineers. For mobile electric power, a new generation of designs will appear. These will be fully simulated and optimized with engineering simulation tools. This should reduce design time and produce a more optimized product than ever before.

The other category of simulation benefits is in training the soldier. Exciting advances occur almost daily in this field. Real time interactive simulations are entering the training environment, from individual soldiers learning marksmanship to flag officers conducting Command Post Exercises so realistic that message traffic must be labeled “Exercise Only” to avoid confusion with real-world traffic. Soldiers can practice again and again in conditions that improve their effectiveness in battle. In the case of mobile electric power, the training tasks are, in general, operation and maintenance. Simulation capabilities are sufficiently advanced as to change the basic question from whether a training simulation can be done to whether it should be done. Does a simulation accurately imitate the expected conditions? Does it help the soldier prepare for the actual event? Can the training can be better performed (cheaper or more thorough) on the equipment itself? At any rate, training simulations will become commonplace for a wide range of equipment, mobile electric power included. As a new generation of mobile electric power is designed, training simulations should become part of the procurement process.
Bus architectures
A host of bus architectures for various purposes now exist. As information technology enters ever more deeply into the operation of many pieces of equipment, appropriate bus structures will either be originated or adapted. For example, SAE J2366 bus has become quite common in automotive equipment. CANbus has become popular with those who prefer a serial approach to factory automation. SMbus is an appropriate serial bus structure for “smart” batteries. IEEE488 governs asynchronous automated instruments and data collection. These four examples illustrate four quite different bus structures for four quite different sets of tasks: a noisy environment with several diverse pieces of equipment, automated control of a factory floor with minimal wiring, an internal data transfer from sensors, and sophisticated two-way communication and control of smart equipment. There are, of course, other bus architectures for many other purposes.

Mobile electric power will become part of a system whose performance can be strongly enhanced by information technology. As such, appropriate bus architectures must be chosen for various facets of its operation: control of the prime mover’s fuel conversion process, control and timing of the power electronics, storage and communication of operation and maintenance data, etc. Appropriate architectures will become more sophisticated, more capable, and more common in the next twenty years. Architectures will span large portions of an industry, enabling manufacturers to field a great number of off-the-shelf pieces of equipment to perform a wide range of coordinated functions. One need only look at CANbus for an example of the concept.

It is difficult to predict which bus architectures will be best. That far in the future, it is likely that the best will be bus architectures that do not yet exist. At any rate, tactical mobile electric power will become more and more a part of an integrated power and communications system in the next twenty years. Choice of compatible bus architectures will become important in processing the data generated on the unit and communicated to other equipment, to operators, and to maintenance people.

Display technologies
Tactical mobile electric power will have more displays than it now does. Displays will be on the unit for operator use and on-site maintenance. Small, thin, rugged displays now handle graphics and text. There will be interface from the unit to displays on laptop computers, both on-site and in remote maintenance shops. 3-D imaging will be here by 2015, perhaps as much as a decade before then. Carbon nanotube technology is targeting displays as its first significant niche application. If successful, this will lead to very thin, high resolution, low power displays. Display technology is mentioned in more detail in Section VI of this report.

Far greater than the influence of any of these individual enhancements will be the effect of advances in information technology. On a grand scale, advances in information technology will transform the legacy force into the Objective Force. Information technology will likewise revolutionize the effectiveness of tactical mobile electric power. It will greatly change the system design, interface to other equipment, operation in the tactical environment, and maintenance procedures and methods. These changes are discussed in the next section of this report.
Section VI
Information Technology

Introduction
Advances in information technology will transform tactical mobile electric power. These technological advances are of the same nature as those that will transform today’s soldier into the Land Warrior and eventually, the Objective Force Warrior. On a much grander scale, the same kind of advances in information technology will transform the legacy force into the Objective Force. This transformation of tactical mobile electric power is significant enough to merit its own section of this report.

US forces can expect to gain strong advantages through effective use of information technologies, many of which will be fielded during the next two decades. For example, the Objective Force Warrior will have a host of information technologies, such as advanced sensors, communication devices, position determination, imaging technology, and computation equipment. The same technologies will transform how electric power is generated and distributed in support of the warfighter. There has been a growing propensity to address performance issues in technologies germane to tactical mobile electric power by intelligently and rapidly applying information technology to the problem. A fundamental level of information technology can be added to the generator itself. These include advanced sensors, human factors and status indication, datalogging, advanced microprocessor control of equipment operation, display technology, and maintenance diagnostics. Wireless communication of maintenance information (sensors, audio, and video) to higher echelons enables remote interactive troubleshooting, more effective dispatching of maintenance personnel and equipment, and more efficient logistical planning. Taking this communication one step beyond intelligent organizational maintenance management, information technologies should also include software to turn data into better decisions and policy innovations. Advanced information security is an important part of this entire system. In other words, tactical mobile electric power generation will be characterized by unprecedented use of information technologies in the effective conversion and distribution of electrical energy.

Information technologies for automatic control in real time
Advanced microprocessor-based control technology has revolutionized the generation and distribution of electrical power in industry. Embedded microprocessors now control nearly every aspect of the electrical side of the process and have become increasingly common on the mechanical and chemical portions. What was knobs, dials, and handwritten reports just fifteen years ago is now all completely automated. As is described in the internal combustion engine subsection of this report, the effect of these technologies is just beginning to be felt.

Control engineers have developed sophisticated methods over the past half century. Only a relative handful of these methods were implemented with the available technology. Most remained solely on paper, beyond the capability of existing hardware. Examples include neural networks, fuzzy logic, feedforward methods, various computational optimization algorithms, etc. For example, the PM electric generator becomes competitive through the use of advanced control and signal processing technologies. These methods have a great deal of merit, but they required fast computation and lots of it for real-time control. Until recently, that was a roadblock to implementing many ideas.

Initially, mechanical systems and analog electrical circuits were the primary means of implementing those ideas that proved to be practical. As the computer became common, digital control supplanted analog methods. By the 1980s, embedded microprocessors and advanced gate arrays began to make distributed control practical. In the past couple years, hybrid combinations of microprocessor cores, digital signal processing, programmable logic, and memory have greatly enhanced computation capabilities in embedded systems. A number of these are already on the market. This trend will continue with an entire system on a chip as the goal: sampling and data conversion, computation, logic, memory, output interfaces, and power supply all on the same chip. Some small companies began this effort, but Intel has become significantly involved within the past year. The ITRS shows an operating frequency of 13.5 GHz and 4.3 billion transistors per high performance microprocessor chip by 2014. The capabilities of embedded processors usually lag the high performance ones by 5-7 years. This means that embedded processors will have about 5 times the speed and 20 times the transistor count that today’s high-end processors have. The combination of system on a chip architectures and faster processors enables even more sophisticated algorithms for control and operation. Communication methods that are being developed for the same signal processors enable a larger and more sophisticated system approach as well.
Advanced digital signal processing hardware has provided the ability to process information rapidly in real time for a host of industrial processes. For example, the development of advanced means of creating intelligent motion has revolutionized the process control industry. Power electronic drive systems are at the heart of this, moving great quantities of products quickly and with great accuracy. One need only observe how potatoes are processed into french fries to understand the power of advanced digital signal processing to control power electronic motor drive systems. Early versions of these same power electronic drive systems are at the heart of AMMPS. Future versions will be able to follow optimum torque and speed profiles of the prime mover and generate more accurate voltage and current waveforms that need less filtering. In fact, the technology to do this already exists in high-performance motor drives. Recently, interest in matrix converters has returned because advanced digital signal processing hardware is finally being built capable of implementing designs that have been restricted to theoretical calculations for decades.

Though certain control methods can be of a general nature, such as those mentioned above, there are also implementations that are specific to a given kind of system. Therefore, within the individual power technology sections of this report, occasional examples are presented of the future of information technology for each respective power technology.

**Information technologies for status reporting and maintenance management**

Information technology first interfaces to humans in the realm of status reports and organizational maintenance management. Here, information technology can make a great impact on the effectiveness of tactical mobile electric power. This is where some important technological advances apply to the generation system directly. These include advanced sensors, indicators and displays, human factors, logging of operational data, and maintenance diagnostics. The gain will be perhaps more readily apparent here than in other places.

A number of performance indicators can be sensed and their sampled values recorded. Candidates for this include temperatures, fuel consumption rates, intake and exhaust flows, pressure, speed of moving parts, voltages, currents, location (from a GPS sensor such as all Automated Teller Machines (ATM) have), etc. Sensors for these purposes already exist. Miniaturization, speed, and accuracy are already quite good and significant improvements are expected to keep pace with applications. Wireless sensors are being built, often saving weight and “spaghetti”. Intermittent sensors with their own energy supply are also in production. For example, a wireless brake temperature sensor on new 2002 model Cadillacs uses a thermoelectric module to provide power only when the brakes heat up because that’s the only time that the sensor needs to provide information. Sensorless methods are being developed for a number of applications. These methods were originally intended to reduce the number of sensors and their cost. (Usually, they do only the former.) For example, high performance electric machines systems have been the subject of intense research into sensorless position determination techniques for the past decade. Recently, comparing the data gathered by such sensorless techniques with data from position sensors has been proposed to improve fault tolerance. This application appeared at a conference in 2002 and is expected on high performance commercial electric motor drive systems within five years.

Display technology has improved significantly, led by demand in the personal computer industry. One need only look at a new top-of-the-line laptop computer to discover the latest advances in bright, thin, and lightweight displays. Developments in avionics design illustrate a twofold set of improvements in display technology: sophisticated, rugged display technology and innovative human factors work. Instead of large numbers of dials, gauges, buttons, and lights, new aircraft have only a few conveniently placed displays. These displays are bright and large enough to be read quickly and easily. They are rugged enough to take repeated takeoffs and landings. They are light enough to be used on aircraft. Another example of the use of new display technology, this one in the maintenance of mobile electric power equipment, is found on the Long Island Railroad. There, technicians receive diagnostics and maintenance instructions by downloading logged data from a data port on railroad cars and locomotives. Then, processing that data through software on a laptop computer display, they take advantage of a sophisticated library of diagnostics and maintenance instructions. Wireless upgrades are budgeted in two years.

An interactive three-dimensional imaging and display system is probably less than ten years away.

With the progress in display hardware, the research effort has by no means neglected the software. Advanced methods are being developed to generate the desired images and show them in a logical and effective format.
Innovative human factors has provided convenient and sensible display of large amounts of data. For example, again in aircraft displays, relevant and carefully selected combinations of indicators appear on appropriate “pages”. Touch panels and other inputs are placed logically for use. Navigation is carefully considered to be intuitive and convenient. Another example of this is the screen displays available to dispatchers in the electric power industry. In both cases, design for emergency situations is carefully engineered for minimum operator effort.

In the past decade, a thousandfold improvement in data memory capacity and speed of access has occurred, both for random access memory (RAM) and for archival storage. By 2015, a hundredfold improvement is predicted for storage capacity and almost as much for processing speed. This has led to a great increase in systems that employ some form of datalogging. For example, datalogging, increasingly using wireless communication, has become ubiquitous in physical plant work (or facilities engineering). Ten years ago, datalogging was awkward, requiring cumbersome equipment and techniques. Now, few physical plant engineers are without datalogging and the display technology that goes with it. Detailed information on the operation of every subsystem on a campus is available to a facilities manager, usually in a conveniently displayed format. In the next twenty years, such systems will grow increasing more convenient and cover more and more details of system operation. For example, all microturbine generator sets log a number of important pieces of operating data. They display these on a panel on the unit itself and communicate the information on an RS-232 link to a central monitoring and control computer.

The utility industry, for example, monitors and logs a host of data at each substation. They transmit some data, such as fault indicators, to a central location. Most of the data stays inside the substation. Information gathered in this manner is fed into maintenance diagnostic software. Sophisticated protection equipment on site, using embedded microprocessors, identifies trends and unusual events and determines appropriate responses to complicated patterns of behavior. If the engineers at company headquarters need the information, they retrieve it at will through a number of means: power line carrier, telephone, microwave link, and wireless. Cell phone technology is replacing microwave links. Only the results, not all the raw data unless requested, is communicated to control and engineering centers. When serious trouble occurs, such as a tripped circuit breaker, appropriate data can be assembled and remotely downloaded remotely to forensic analysts. For new substations, everything is designed and assembled in a substation manufacturer’s factory and delivered as a turnkey system to the substation. These capabilities are available now; the big question is how many of them will be affordable for medium-sized generators by 2015.

The railroad industry provides a final example of maintenance diagnostics for this discussion. Locomotives are a mobile electric power system, having diesel power plants that drive electric generators. These generators in turn drive the wheel motors and provide electrical power for all the control and sensor equipment in the train. Each piece of equipment on board and even the sag of the track is appropriately monitored as the train moves along. Trends and unusual events are identified and wirelessly communicated to control centers, even trouble indicators that human operators would normally miss. For example, a 15% change in fuel consumption rate is barely noticeable to the operator, but indicates certain maintenance problems. But a Union Pacific locomotive that exhibits this symptom while rolling eastward somewhere near Cheyenne will find a repair crew waiting with the correct repair parts in hand when the locomotive arrives in Minneapolis. The problem had been diagnosed, wirelessly communicated a thousand miles, and a maintenance crew automatically scheduled without involving the operator at all. It is this kind of performance that information technology will provide for mobile electric power within twenty years. It is already available. Advances in processor technology may make it affordable for tactical mobile electric power within a few years.

Such maintenance systems provide a great opportunity for the next generation of mobile electric power in the medium power range. If a generator experiences trouble, the operator can download logged data to a personal computer (or use a display mounted on the generator) to receive operator-level maintenance diagnostics and instructions stored. Organizational maintenance can be notified of trouble automatically or in response to operator inquiry. Organizational maintenance receives the appropriate data through a wireless link and performs its own diagnostics remotely. Some actions can be completed remotely, such as tuning and making adjustments or switching to backup equipment. If a problem requires a repair technician to travel to the site, organizational maintenance diagnostics will have already identified the problem remotely, selected and drawn the spare parts for the technician, reordered replacement stock, used GPS data for an exact location and safe route, and downloaded the necessary repair instructions and manuals (or sent them wirelessly ahead). If evacuation is necessary, the technician
may make that determination without leaving the maintenance shop. This dramatically reduces the risk of putting scarce repair technicians on the road, a dangerous practice employed too often in many tactical units.

Information technologies provide tactical mobile electric power with the tools to greatly enhance performance. Status information can be sent to maintenance or command elements wirelessly and automatically. Advanced diagnostics will provide more efficient operator and organizational maintenance. Display technology with enhanced human factors interfaces helps illustrate status and problems, winnowing the data appropriately. These capabilities should be available and affordable by 2015 and will strongly enhance the performance of tactical mobile electric power.

**Information technologies for policy determination**

Interactive status reporting and maintenance diagnostics with wireless communication and display methods are important information technologies for mobile, medium sized electric power generation. Many of those technologies already exist and many of them are already on the market. Incorporating those technologies is actually the easier part of using information to improve the performance. The harder part is winnowing a mass of operation and maintenance data, using the results to make policy decisions. Subsets of this problem include identifying trends, formulating results for display to policy makers, using advances in understanding cognition and decision making processes, and automatically creating policy innovations.

Trends in maintenance of a given piece of equipment can be picked up from data leveled across very large units, such as Corps and above. A reasonable feature to include in maintenance management software is an automatic reporting capability, routinely sending a report of every diagnosis to a central collection point within a command. Mining such information from a large amount of data is a fundamental task for advanced decision aids. In this way, unusual trends could be identified early and action taken within the command or forwarded to the Army’s laboratory structure to identify fixes. Data mining software already exists, though rudimentary at present, and should advance somewhat in the next twenty years.

Another place where information technologies can directly lead to policy innovations is in the research and development process. Often, a researcher lacks adequate information on how legacy systems perform in the field. For example, software is fielded for power management of a certain tactical electric power generator. However, data on this system as it performs in the field is not easy to gather with existing technology. The Hawthorne Effect degrades data quality even when data are gathered. The researcher too often has two undesirable options: use simulated inputs based on weak assumptions or use data of questionable quality. Having automatic data collection in place on equipment will provide better quality information to the researcher. For specific sets of information, programming could even be done before a field exercise. The preceding is but one example of how information can be specifically requested with minimal impact on training and operations.

A great deal of research is underway in winnowing and displaying results for decision makers. Much of the emphasis is on getting relevant information to the commander in a concise and timely fashion, overcoming information overload. This is the realm of the soft sciences where we understand learning, cognitive processes, task analysis, decision-making, and situation awareness. An example of such methods is software that integrates human operators with advanced automation and decision support technologies. It also includes development of meaningful measurement techniques. Fortunately, developing these decision systems is not a task solely for those involved in mobile electric power. Rather, mobile electric power can leverage this technology from those who develop it for control and analysis of operations.

In the 1980s, Robert Solow, the MIT Nobel-Prize winning economist, visited the problem of formulating policy from large quantities of information about a business’s operations. He concluded that computers are found everywhere but in the productivity statistics. In other words, advanced information technology had yet to influence policy decisions directly. He revisited this problem in the late 1990s and found significant changes. He found that Wal-Mart had developed ways to convert data on inventory and operations into innovative managerial and organizational policy. Innovations include methods of electronic data exchange, economies of scale and timing in warehouse logistics and purchasing, and wireless bar code scanning. Dr. Solow’s MIT study concluded that Wal-Mart’s ability to do this was the single greatest contribution to US productivity between 1995 and 2000. Wal Mart, as of April 2002, is the largest corporation in America, surpassing Exxon in total revenue. Therefore, successful
methods of converting great quantities of data into innovative managerial and organizational policy now exist. This should be a subject of further investigation and leveraged into the next generation of tactical mobile electric power as well as other military equipment.

**Information technologies for networking of generators**
The most important goal of the electric utilities since the end of World War II has been reliability: an absolute minimum number of interruptions affecting an absolute minimum area for an absolute minimum time. Networking electric power generators strongly enhances power system reliability. That’s why the public utilities do it. That’s also a good reason to consider it for tactical mobile electric power.

In the past, small to medium-sized generating systems have not been networked. Small power generators have typically not been stable enough to make networking practical. The control systems necessary to maintain synchronism and regulate power flow have been too expensive. Networking also requires costly circuit protection. Nonetheless, recent advances in information technologies may change that situation or at least lower the threshold power level at which networking becomes affordable.

AMMPS generates its output voltage waveforms by Pulse Width Modulation. Frequency and voltage are quite stable in even the smallest units. The next generation of generators will have even better frequency and voltage regulation. It will also have the advantage of improved embedded microprocessor technologies. If voltage and frequency can be closely regulated in small generating units, then power flow can be regulated in networks composed of those small units.

The first question is whether appropriate technology even exists in this power range. In systems of distributed generation that are popular in remote wilderness locations, several unlike power sources are often networked together. These may be, for example, a diesel generator, a wind turbine, battery storage, an inverter, and active power management of the load. They have a grid interface and contain elementary circuit protection. All resources are rated in the medium power range, typically less than 5500 Watts. Each resource is programmed for conditions of load, temperature, wind speed, and other sensor inputs. These are all controlled from a single microprocessor. Xantrex Trace Engineering has been selling reliable units for this purpose for several years. So have other vendors. Therefore, reliable technology exists for inverter-based systems in this power range and will improve over the next several years.

Circuit protection would be primarily against overcurrent problems. Appropriate equipment already exists for this purpose. Schweitzer Engineering of Pullman, Washington, already has microprocessor-based circuit protection equipment that would be appropriate for systems of larger networked generators. That equipment is readily programmable to handle the flexibility necessary for the anticipated operational tempo. The Navy is working on interconnected zonal protection algorithms in electric power systems that have only a few generators. These algorithms enable networked generators to survive the multiple faults that an enemy shell might cause while automatically reconfiguring the generators and loads for maximum survivability. However, these probably won’t be available until about 2030. On the other hand, Capstone Microturbine already has coordinated overcurrent protection on its networked microturbines. It is digital in nature, based on Hall sensors. This means that it is both quite fast and programmable. Therefore, circuit protection in small systems will exist in 2015 and will be fairly fast and responsive, but probably not as sophisticated as a ship would require.

Communicating the necessary signals to network the generators can be done. The Navy already has such networked multiple-generator systems with appropriate automated protection. However, they are large and the coordination and protection are expensive.

The question remains whether a networked system is practical. If an inverter is already part of the each generator, as it is with AMMPS, then there is little additional weight. Circuit breakers must be digitally controlled in a networked system. Fortunately, off-the-shelf circuit protection equipment already exists. A networked system requires power flow control software that has been available only at somewhat higher power ranges, but advanced embedded microprocessors can be programmed to do the control work. Distances are sufficiently short, allowing communication to a central network controller. However, a networked system would have to be fairly flexible, accommodating various numbers of generators and requiring an ability to add or delete a generator or two from time
to time. It would also require control of a “spinning reserve”. The Xantrex Trace unit does this by clever use of a
dc link and energy storage. Therefore, the complexity and cost of a networked system of small generators probably
keeps such a system out of reach by 2015. However, it may not be so unreasonable by 2030.

Advanced information security
There is little doubt that the enemy will engage in information warfare. Without advanced information security,
many of the advantages provided by information technology will not always be available. Information technologies
that will enhance the effectiveness of Objective Force Electric Power rely on signals that are vulnerable to detection,
interference (intentional or otherwise), interception, and deception. Just as the technology is more powerful, so the
effects of inadequate security can be all the more disastrous. COL Thaddeus Dmuchowski, Director of the Army’s
Information Operations Assurance Office, explained this dramatically, “It is conceivable, in theory, for a hacker
sitting in his easy chair to get inside a tank!”

For Objective Force Electric Power, nearly all of the information that passes from place to place is logistical in
nature: status, position, maintenance diagnostics, displays, repair commands, etc. Logistics systems have
historically tended to be less well secured than command and control systems. Logistics systems gained a measure
of security from the difficulty of processing great amounts of low-quality intelligence, just as lighter security was
often feasible at lower levels of command due to the rapidly perishable nature of information there. Those
assumptions may no longer be true. Therefore, advanced information security will be necessary to preserve the
advantage that information technologies afford.

Conclusions
Advances in information technology hold the promise of transforming tactical mobile electric power completely.
High speed microprocessors and logic arrays, including hybrid technologies, finally have become able to implement
a wider range of advanced control algorithms. As a result, machinery will be able to do far more in the next twenty
years. AMMPS is but the first step. Information technology will enable significant advances in sensors, indicators
and displays, human factors, logging of operational data, and maintenance diagnostics. The result will be greater
equipment reliability through remote troubleshooting and a more responsive organizational and support maintenance
system. Collection of data for research and policy development is a harder thing, but advances will be made as
mobile electric power partners with others. Networking of small generators is possible, but the cost may be too high
this soon. It will be an exciting time as tactical mobile electric power experiences a transformation that is but a
microcosm of the transformation of the entire force.
Section VII
Conclusions

Evaluation
Tactical environment and criteria
The doctrine was carefully considered and analyzed to determine how tactical mobile electric power fits into what we want to do. Several requirements for tactical mobile electric power came to light from that analysis. The details of that analysis are in Section II, Tactical Considerations.

1. A single underlying basic design
2. Power upon demand
3. Easy to interface, but accommodates a wide range of loads
4. Anticipates the impact of new technologies
5. Avoids overdesign by modularizing any special capabilities
6. Provides excellent fuel efficiency from highly reliable and maintainable equipment
7. Fits into a knowledge-based C4ISR system architecture
8. Easy for the soldier to install, operate, and maintain
9. Affordable acquisition and life cycle costs.

Using the force design principles set forth in doctrine, a set of evaluation criteria was selected as a basis for review of the chosen power technologies. These criteria are defined in some detail in Section II, Tactical Environment. The list includes the following:

<table>
<thead>
<tr>
<th>Deployability</th>
<th>Survivability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>Safety</td>
</tr>
<tr>
<td>Size (Volume)</td>
<td>IR Signature</td>
</tr>
<tr>
<td>Energy Density</td>
<td>EMI signature</td>
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<tr>
<td></td>
<td>Audible Signature</td>
</tr>
<tr>
<td></td>
<td>Visible Signature</td>
</tr>
<tr>
<td></td>
<td>Human factors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Versatility</th>
<th>Sustainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalability</td>
<td>Cost</td>
</tr>
<tr>
<td>Environ. Compatibility</td>
<td>shelf life</td>
</tr>
<tr>
<td>Reliability</td>
<td>Maintainability</td>
</tr>
<tr>
<td>Mobility</td>
<td>Production base</td>
</tr>
<tr>
<td>Availability</td>
<td>Remedy defects?</td>
</tr>
<tr>
<td>Start/restart</td>
<td>Environ. impact</td>
</tr>
<tr>
<td>Energy storage?</td>
<td>Political impact</td>
</tr>
<tr>
<td>Step response</td>
<td></td>
</tr>
<tr>
<td>Length of service</td>
<td></td>
</tr>
<tr>
<td>Peak factor</td>
<td></td>
</tr>
<tr>
<td>Duty cycle</td>
<td></td>
</tr>
</tbody>
</table>

Available technologies
A list of candidate technologies was assembled. Some were obviously inappropriate and given no further consideration. However, several were reasonable candidates.

- Internal combustion engine with rotating generator
- Turbine with rotating generator
- Fuel cell, with and without reformer
- Thermophotovoltaic
- Radioisotope with thermal generator
- External combustion
- Energy harvesting (wind, photovoltaic, biomass, human, hydro, geothermal, wave, tidal)

Each of these was investigated in some depth. Experts from government, academia, and industry were consulted for their insight and recommendations. An extensive search of the literature yielded important insights into the present
state of these technologies and their expected futures. The list of sources is given in Acknowledgements at the beginning of the report. The conduct and results of that investigation are described in Section III, Energy Technologies. A table showing the weighted results is at the end of the same section of this report. The following conclusions became apparent from this investigation.

1. Place the most emphasis on the internal combustion engine and the microturbine. These are the technologies that work best today. New information technologies will enhance these to a degree that competing technologies will have difficulty keeping pace, let alone gaining ground. Appropriate tactical fuels will be available in sufficient quantities throughout the time period under consideration.

2. Continue to monitor fuel cell progress. There are two divergent routes that could make the fuel cell competitive, given significant breakthroughs. Because hydrogen fuel cells already exist as OEM equipment, the first route is through advances in hydrogen generation and storage. The second route is through advances in reformer technology that enables the use of tactical fuels. Methanol as a fuel will likely be quite practical by 2015 and gasoline may be a possibility for reformer-based fuel cells by then. Tactical fuels are not likely without a breakthrough and conditions for finding that breakthrough are not likely to occur.

3. Be able to leverage fuel cell progress quickly if it does occur. The automobile companies are creating a research environment where breakthroughs are quite possible. We should be alert to capitalize upon them if they occur.

4. Energy harvesting, such as photovoltaics, will fit into hybrid systems, but will not be able to support a system of 500 Watts to 10kW alone. Hybrid systems are a reasonable means of incorporating new technologies into the inventory.

Energy storage
Several of the power technologies require energy storage to perform well. Therefore, this investigation also identified several possible means of energy storage for support of tactical mobile electric power.

- Chemical batteries
- Ultracapacitors
- Flywheels
- Superconducting magnetic energy storage
- Pumped fluid storage

Similar consultations and searching of the literature led to some conclusions about which means of energy storage would be most effective. Details of the investigation and analysis is presented in Section IV, Energy Storage.

1. Chemical batteries provide the most effective means of energy storage
2. Combining chemical batteries with ultracapacitors yields the combined advantages of the faster response of the ultracapacitors and the energy storage of the chemical batteries. In cases where the added expense is acceptable, this combination dramatically improves performance.

Performance enhancements
There is a host of technologies that enhance performance of power generation and energy storage. They are called enhancements in this report because improvements in these technologies enhance the performance of more than one power generation or energy storage technology. Among the more promising enhancements are the following, each of which is addressed in more detail in this section of the report:

1. Power management, as described in the vision statement
2. Hybrid electric vehicle technologies
3. Uninterruptible power supply technologies
4. Fuels
5. Selection of electric machine topology
6. Power Electronics
7. Advanced nonlinear control
8. dc microgrid technology
9. Protection of networked generators: efficiency and redundancy
10. Effects of server load
11. Though time did not permit a detailed investigation, the following are also mentioned: Materials, Lubricants and lubricant-free technology, simulation, bus architectures, and display technologies. These are addressed in some detail within other sections of the report as well.

Information technology transforms tactical mobile electric power
Information technology is transforming the soldier system, transforming the legacy soldier into the Objective Force Warrior. On a grand scale, information technology will transform the legacy force to the Objective Force. The final section of this report addresses several aspects of information technology as they apply to tactical mobile electric power. The impact is so great that this merits its own section of the report.

- Information technologies for automatic control in real time
- Information technologies for status reporting and maintenance management
- Information technologies for policy determination
- Information technologies for networking of generators
- Advanced information security

These are broad topics that require a lot of further research. However, a clear conclusion is that we must apply information technology enhancements to improve operation, maintenance, and decision-making. Just as information technology is transforming the soldier system, so it must transform tactical mobile electric power generation if we are to remain competitive.

**Recommendations**

**Performance Drivers**
The performance drivers are the 72-hour autonomous operation requirement, size and weight, reliability and maintainability, and signature reduction. The system should operate for 72 hours without resupply. Size and weight must be kept to a minimum to enhance deployability. Reliability and maintainability mean the system will give power upon demand and will continue to do so with minimum operator effort. Signature reduction fits the system better into the tactical environment.

**Internal combustion engine with rotating generator**
The internal combustion engine will likely remain the leading alternative to drive a tactical mobile electric power system. This will be due to expected advances in materials, fuels, and control technology based on intelligent use of information. In fact, a publication as prestigious as the Proceedings of the IEEE acknowledges in December 2001 that the stream of technological innovations expected in internal combustion engines poses a substantial problem for competing technologies for the foreseeable future. Its primary disadvantage is its acoustic noise.

A permanent magnet (PM) machine will be dominant as a generator in this power range. PM machines have a great deal to recommend them: self exciting, compact, low losses (compared to other machines), and quite rugged. Except for their sensitivity to faults, their shortcomings should be completely resolved by 2015. Advances in power electronics will make this possible. The electric machine in AMMPS is a PM machine.

**Turbine**
The microturbine appears to be one technology that can give the internal combustion engine some serious competition for tactical mobile electric power applications. The microturbine is quieter and more reliable than an internal combustion engine, can operate for 72 hours without attention, has a nearly universal fuel capability, and has already incorporated a great deal of information technology into operation and maintenance. It has a proven record of ruggedness and a longer rated life than an internal combustion engine. The same types of rotating electric machines and power electronics are compatible with both turbine and internal combustion engine. Because it rotates faster than an internal combustion engine, it requires smaller rotating machines. The primary disadvantage is a slower response to changes in load.
Fuel cell
The fuel cell appears to be a long-term technology. Hydrogen fuel cells already exist as OEM equipment and commercially viable reformed methanol fuel cells will likely be available well before 2015. A fuel cell that uses tactical fuels is unlikely within twenty years. The problem is difficult, the military is really the only significant customer, and the great commitment of resources to make breakthroughs happen does not exist yet.

There are two roads to success for the fuel cell: develop the hydrogen storage and distribution technology or develop an appropriate reformer. Both routes require a great investment, but the automobile companies have begun to make that investment. What the automobile companies conclude will be a good indicator of fuel cell feasibility. They should have a fuel cell that works well by 2010 or they will give the fuel cell such a “black eye” that it will not recover for decades.

Energy storage
For mobile electric power in the anticipated tactical environment twenty years hence, rechargeable batteries appear to be the strongest alternative for energy storage. Flywheels have some attractive characteristics, but will remain more bulky and expensive than batteries. SMES is likewise heavy and expensive, awaiting a breakthrough in superconductors that reduces the refrigeration requirement. Hybrids, such as battery-capacitor combinations, will become more attractive as they improve the responsiveness of energy storage systems while maintaining the capacity.

Power management
Power management holds great promise for reducing electric power demand. Without it, the growth in power demands may drive the goal of 72 hours completely beyond reach. Through power management, new power technologies can become practical pieces in an integrated system. We will need them: if we are to go 72 hours, every scrap of energy will be at a premium. Because design practices, as well as tactics, techniques, and procedures, are not yet optimized for power management, improvements gained by employing it may initially be quite significant. A factor of 2 improvement appears to be quite realistic before 2015. An eventual factor of 10 improvement is probably not.

Power management must be engaged in both static and dynamic realms. When designing equipment, energy conservation must be defined clearly and optimized aggressively against other performance measures under the supervision of a unified design authority. Real time measures to conserve energy must be aggressively pursued, such as software enhancements and training the warfighters to work with their equipment to save energy wherever possible. A fully resourced power management office with total responsibility for power management policy and implementation will help achieve this unity and discourage a piecemeal defeat of power management.

Advanced power electronics
A key to the technical side of tactical mobile electric power is the use of advanced power electronic converters. The converters that the Army seeks are already available from industry: electric drives and Uninterruptible Power Supplies (UPS) manufacturers. These folks have been doing reliable, rugged power electronic converters for many years. They have the advanced control methods of control, interfacing, and circuit protection at the point of application, with linked embedded processors. Many of their units are modular. They have advanced methods of controlling hybrid electrical energy systems and distributed generation and these will be commonplace in their products long before 2015. This is the same technology that may enable networking of generators at a tactical site, greatly improving the reliability of tactical mobile electric power.

Information technologies
Advances in information technology hold the promise of transforming tactical mobile electric power completely. High speed microprocessors and logic arrays, including hybrid technologies, finally have become able to implement a wider range of advanced control algorithms. As a result, machinery will be able to do far more in the next twenty years. AMMPS is but the first step. Information technology will enable significant advances in sensors, indicators and displays, human factors, logging of operational data, and maintenance diagnostics. The result will be greater equipment reliability through remote troubleshooting and a more responsive organizational and support maintenance system. Collection of data for research and policy development is a harder thing, but advances will be made as
mobile electric power partners with others. Networking of small generators is possible, but the cost may be too high this soon.

**Future of Tactical Mobile Electric Power**

Vice President Cheney has said that the new economy runs on electricity. We might add that so will the transformed Army. It will be an exciting time as tactical mobile electric power experiences a transformation that is but a microcosm of the transformation of the entire force.

**Summary Chart**

On the following two pages, a chart shows a summary of recommendations. This includes each technology: basic energy conversion, energy storage, performance enhancements, and information technology. Available time frame indicates when the technology in some form will be available. With time, most technologies should advance as described in this report. Exceptions are noted in the comments line. Whether the technology is broadly feasible for military use in the 2015-2025 time frame is indicated and whether further effort will either hasten its adoption for military use. Comments summarize key points made in this report. This summary is intended to provide a quick and simple guide to findings.
<table>
<thead>
<tr>
<th>Name of Technology</th>
<th>Available Time Frame</th>
<th>Military Feasibility</th>
<th>Recommended for Further Effort</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Combustion</td>
<td>Now-2025</td>
<td><strong>yes</strong></td>
<td><strong>yes</strong></td>
<td>Information and control technologies likely to keep this dominant</td>
</tr>
<tr>
<td>Turbine</td>
<td>Now-2025</td>
<td><strong>yes</strong></td>
<td><strong>yes</strong></td>
<td>Very strong alternative to IC engine: quieter, multifuel, low maint</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tactical fuels</td>
<td>Beyond 2030 perhaps</td>
<td><strong>no</strong></td>
<td><strong>yes</strong></td>
<td>Unlikely due to insufficient funding and civilian industry interest</td>
</tr>
<tr>
<td>reformed methanol</td>
<td>~2010</td>
<td><strong>yes</strong></td>
<td><strong>yes</strong></td>
<td>Will be generally available by 2015</td>
</tr>
<tr>
<td>direct methanol</td>
<td>Beyond 2020 perhaps</td>
<td><strong>no</strong></td>
<td><strong>yes</strong></td>
<td>Short life, complicated and generally unreliable</td>
</tr>
<tr>
<td>hydrogen</td>
<td>Now-2025</td>
<td><strong>no</strong></td>
<td><strong>yes</strong></td>
<td>Available now. Needs better storage and distribution technology.</td>
</tr>
<tr>
<td>Thermophotovoltaics</td>
<td>Now-2025</td>
<td><strong>yes</strong></td>
<td><strong>yes</strong></td>
<td>Useful in hybrid situations</td>
</tr>
<tr>
<td>Radioisotope</td>
<td>Now-2025</td>
<td><strong>no</strong></td>
<td><strong>no</strong></td>
<td>&gt; 72 hours, bulky and politically unacceptable, little advance expected</td>
</tr>
<tr>
<td>External Combustion</td>
<td>Now-2025</td>
<td><strong>no</strong></td>
<td><strong>no</strong></td>
<td>High efficiency, low noise, heavy, not power on demand</td>
</tr>
<tr>
<td>Energy Harvesting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>human</td>
<td>Now-2025</td>
<td><strong>no</strong></td>
<td><strong>no</strong></td>
<td>Not feasible for &gt; 500 Watts</td>
</tr>
<tr>
<td>biomass</td>
<td>~2010</td>
<td><strong>no</strong></td>
<td><strong>no</strong></td>
<td>Difficult to deploy</td>
</tr>
<tr>
<td>photovoltaic</td>
<td>Now-2025</td>
<td><strong>yes</strong></td>
<td><strong>yes</strong></td>
<td>Strong possibility for hybrid. Needs large area and storage</td>
</tr>
<tr>
<td>wind</td>
<td>Now-2025</td>
<td><strong>no</strong></td>
<td><strong>no</strong></td>
<td>Cheap and available. Awkward to deploy, needs energy storage</td>
</tr>
<tr>
<td>Rechargeable Battery</td>
<td>Now-2025</td>
<td><strong>yes</strong></td>
<td><strong>yes</strong></td>
<td>Best available energy storage and likely to remain so</td>
</tr>
<tr>
<td>Ultracapacitors</td>
<td>Now-2025</td>
<td><strong>yes</strong></td>
<td><strong>yes</strong></td>
<td>Excellent speed of response. Useful for hybrids with batteries also</td>
</tr>
<tr>
<td>Flywheel</td>
<td>Now-2025</td>
<td><strong>yes</strong></td>
<td><strong>yes</strong></td>
<td>Lots of storage. Excellent response. Heavy and expensive.</td>
</tr>
<tr>
<td>SMES</td>
<td>Now-2025</td>
<td><strong>no</strong></td>
<td><strong>yes</strong></td>
<td>Heavy and requires expensive refrigeration; lots of storage</td>
</tr>
<tr>
<td>Pumped Storage</td>
<td>Now-2025</td>
<td><strong>no</strong></td>
<td><strong>no</strong></td>
<td>Large, fixed plants only</td>
</tr>
<tr>
<td>Name of Technology</td>
<td>Available Time Frame</td>
<td>Military Feasibility</td>
<td>Recommended for Further Effort</td>
<td>Comments</td>
</tr>
<tr>
<td>----------------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>--------------------------------</td>
<td>----------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Power Management</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>Need unified, fully resourced authority; vehicle to integrate new tech</td>
</tr>
<tr>
<td>Hybrid Electric Vehicle</td>
<td>~2007</td>
<td>yes</td>
<td>yes</td>
<td>Eliminate most trailer-mounted generators, has a capable silent mode</td>
</tr>
<tr>
<td>Power Quality / UPS</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>Has developed mitigation technology for most energy storage issues</td>
</tr>
<tr>
<td>Fuels</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>Proven reserves of fossil fuels will last past 2025</td>
</tr>
<tr>
<td>Electric Machine</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>Permanent magnet machine will dominate; variable speed operation</td>
</tr>
<tr>
<td>Power Electronics</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>DC link converter with PWM will dominate</td>
</tr>
<tr>
<td>DC Microgrid</td>
<td>~2010</td>
<td>yes</td>
<td>yes</td>
<td>Linking generators for better reliability</td>
</tr>
<tr>
<td>Circuit Protection</td>
<td>~2020</td>
<td>no</td>
<td>yes</td>
<td>Larger generators may have advanced digital protection by 2020</td>
</tr>
<tr>
<td>Server Load</td>
<td>Growing</td>
<td>yes</td>
<td>yes</td>
<td>Designs will affect location and amount of power demanded</td>
</tr>
<tr>
<td>Automatic Control</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>Makes basic technologies feasible; strongly influences rate of advance</td>
</tr>
<tr>
<td>Maint Mgmt</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>A strong area for significant advancement</td>
</tr>
<tr>
<td>Policy Determination</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>Sets the stage for great future advancements</td>
</tr>
<tr>
<td>Generator Networking</td>
<td>~2030</td>
<td>no</td>
<td>yes</td>
<td>US Navy now leads in this technology</td>
</tr>
<tr>
<td>Info Security</td>
<td>Now-2025</td>
<td>yes</td>
<td>yes</td>
<td>No information technology will work without excellent security</td>
</tr>
</tbody>
</table>

Figure 3. Technology Summary

Front End Analysis
Mobile Electric Power Research and Development for the 2015-2025 Time Frame
Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ac</td>
<td>alternating current</td>
</tr>
<tr>
<td>AMC</td>
<td>Army Materiel Command</td>
</tr>
<tr>
<td>AMMPS</td>
<td>Advanced Medium-sized Mobile Power Source</td>
</tr>
<tr>
<td>AMTEC</td>
<td>Alkali Metal Thermal to Electric Cell</td>
</tr>
<tr>
<td>ARL</td>
<td>Army Research Laboratory</td>
</tr>
<tr>
<td>ASEE</td>
<td>American Society for Engineering Education</td>
</tr>
<tr>
<td>ATM</td>
<td>Automated Teller Machine</td>
</tr>
<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
</tr>
<tr>
<td>C2D</td>
<td>Command and Control Directorate</td>
</tr>
<tr>
<td>CASCOM</td>
<td>Combined Arms Support Command</td>
</tr>
<tr>
<td>CEC</td>
<td>California Energy Commission</td>
</tr>
<tr>
<td>CECOM</td>
<td>Communications-Electronics Command</td>
</tr>
<tr>
<td>CERDEC</td>
<td>Communications-Electronics Command Research, Development, and Engineering Center</td>
</tr>
<tr>
<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
</tr>
<tr>
<td>dc</td>
<td>direct current</td>
</tr>
<tr>
<td>DoE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>FEA</td>
<td>Front End Analysis</td>
</tr>
<tr>
<td>FVFF</td>
<td>Fixed Voltage, Fixed Frequency</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>HP</td>
<td>Hewlett-Packard</td>
</tr>
<tr>
<td>hp</td>
<td>horsepower</td>
</tr>
<tr>
<td>hr</td>
<td>hour</td>
</tr>
<tr>
<td>IBCT</td>
<td>Initial Brigade Combat Team</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IMA</td>
<td>Individual Mobilization Augmentee</td>
</tr>
<tr>
<td>ITRS</td>
<td>International Technology Roadmap for Semiconductors</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>kHz</td>
<td>kilohertz</td>
</tr>
<tr>
<td>kW</td>
<td>kilowatts</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium-ion Battery</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>Ni-Cd</td>
<td>Nickel-Cadmium Battery</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>PM</td>
<td>Permanent Magnet</td>
</tr>
<tr>
<td>PM-MEPP</td>
<td>Project Manager, Measurement, Electric Power, and Protection</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>RDEC</td>
<td>Research, Development, and Engineering Center</td>
</tr>
<tr>
<td>SMES</td>
<td>Superconducting Magnetic Energy Storage</td>
</tr>
<tr>
<td>ST</td>
<td>STMicroelectronics Corporation</td>
</tr>
<tr>
<td>TOC</td>
<td>Tactical Operations Center</td>
</tr>
<tr>
<td>TPV</td>
<td>Thermophotovoltaic</td>
</tr>
<tr>
<td>TQG</td>
<td>Tactical Quiet Generator</td>
</tr>
<tr>
<td>TRADOC</td>
<td>Training and Doctrine Command</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
<tr>
<td>VLRA</td>
<td>Valve Regulated Lead Acid Battery</td>
</tr>
<tr>
<td>VVVF</td>
<td>Variable Voltage, Variable Frequency</td>
</tr>
<tr>
<td>W·hr</td>
<td>Watt-hour</td>
</tr>
</tbody>
</table>
About the author

Lieutenant Colonel Herbert L. Hess received the Bachelor of Science degree from the United States Military Academy in 1977 with a concentration in Applied Science and Engineering. He served with the 125th Signal Battalion in Hawaii for nearly two years as a tactical signal platoon leader supporting the 25th Division Tactical Command Post and the 25th Division Artillery Headquarters. He worked extensively with the MEP generators that dominated the inventory at that time. He then became Communications-Electronics Staff Officer to the First Battalion, 35th Infantry for two years. The infantry deployed around the Pacific, including the island of Hawaii, Australia, the Philippines, and Korea. He provided communications and tactical mobile electric power in a host of tactical environments.

Upon leaving the 25th Division’s light infantry, he earned a Master of Science degree in Electrical and Computer Engineering from the Massachusetts Institute of Technology. His thesis analyzed the Wanlass configuration of the induction motor, providing the definitive analysis of its design and operation. He successfully modeled its performance under a wide range of loads and ratings, including a verified prediction of self-excitation. Upon graduation in September 1982, he became commander, C Company, 304th Signal Battalion. C Company provided secure Corps Area tactical communications and tactical mobile electric power to the Commanding General, US Forces Korea, the Korean Combined Unconventional Warfare Command, and the tactical command bunker of the President of South Korea. After finishing the command assignment, he became Assistant Professor of Electrical Engineering at the US Military Academy, West Point. He taught courses in circuits, microelectronics, electric machines and power electronics, power systems, automatic control, instrumentation, and electronic systems design.

In 1988, he left active duty to commence his doctoral studies in Electrical and Computer Engineering as a Fannie and John Hertz Fellow at the University of Wisconsin. His dissertation on a new, inexpensive method of driving induction machines with thyristors and embedded control led to a patent and four publications. It remains the only known method of using thyristors to achieve full torque at zero speed with fine position control for a squirrel cage induction motor. In 1993, he received the doctoral degree and joined the faculty of the University of Idaho at its Boise Engineering Program. He taught power electronics, electric machines, power systems, automatic control systems, and electrical system design. His work in power supply design led to three patents with Hewlett-Packard for an advanced fuser power supply in laser printers. He was also involved in innovative methods of improving power quality in regional industries such as lumber, dairy products, and irrigation. When the Engineering Program in Boise closed in 1996, he transferred to the main campus where his work continues in power electronic systems. These include micropower supplies and battery chargers (system on a chip) for NASA JPL, advanced induction generator drive systems for the National Renewable Energy Laboratory, and fast fault generation methods and protection algorithms for the US Navy. He has built remotely located generating systems, powered by diesel, wind, photovoltaic, and hydroelectric equipment, and passive heat management. He has over 30 publications in journals and conferences. With Dr. R. Jacob Baker, he developed a method of triggering series MOSFETs which won the IEEE Power Electronics Society’s Best Transactions Paper of the year 2000. He is also Chairman of the Energy Conversion and Conservation Division of the American Society for Engineering Education (ASEE), where he won ASEE Overall Best Paper of the Year in 1999.

Since leaving active duty in 1988, he has remained an Army Reservist and Individual Mobilization Augmentee (IMA). Until 2000, his assignment was on the Staff and Faculty, US Military Academy. The capstone electrical engineering design program there is his contribution, as are significant parts of the electric power instructional laboratory. He has received awards for excellence in teaching at both West Point and the University of Idaho. As a Reservist, he was mobilized for the Gulf War in 1991 and for homeland defense in 2001. He is now an IMA serving an active duty tour as an electrical engineer at the US Army Communications-Electronics Command (CECOM) Research, Development, and Engineering Center (RDEC), Command and Control Directorate (C2D), Army Power Division, Fort Monmouth, New Jersey. He is a graduate of the Army Command and General Staff College. He is a Senior Member of the IEEE, and a Registered Professional Engineer in Idaho and Virginia. He holds a tenured appointment as Associate Professor of Electrical and Computer Engineering at the University of Idaho.