Combat Hybrid Power System Component Technologies: Technical Challenges and Research Priorities

Committee on Assessment of Combat Hybrid Power Systems, National Research Council

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COMBAT HYBRID POWER SYSTEM COMPONENT TECHNOLOGIES

TECHNICAL CHALLENGES AND RESEARCH PRIORITIES

Committee on Assessment of Combat Hybrid Power Systems
National Materials Advisory Board
Board on Manufacturing and Engineering Design
Division on Engineering and Physical Sciences

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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their participation in the review of this report: Andrew Frank, University of California, Davis; Michael Lanagan, Pennsylvania State University; Thomas Matty, SAFT America (retired); Ian McNab, University of Texas; Wilford Smith, SAIC; Joseph Wirth, Raychem Corporation (retired); and Douglas Witherspoon, UTRON, Inc.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by William Agnew, General Motors Corporation (retired). Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Comments and suggestions can be sent via e-mail to nmab@nas.edu or by fax to (202) 334-3718.

Robert Guenther, *Chair*
Committee on Assessment of
Combat Hybrid Power Systems

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Executive Summary

The U.S. Army envisions that many of its future combat vehicles will feature a hybrid electric power system containing a diesel or turbine generator that will supply electric power to operate the vehicle subsystems, including electric drive and weapons systems. In military hybrids, pulsed power and continuous power must operate together without interference. Pulsed power is required for high-power lasers, an electrothermal chemical (ETC) gun, high-power microwave weapons, electromagnetic armor, and other systems. Elements of the continuous power system include prime power (diesel or turbine), generator, motors, converters, power distribution systems, storage, fault protection, safety systems, and auxiliary power connections.

While some of the technologies required to support combat hybrid vehicle power systems are in hand, many technical challenges remain. In 1997, the Defense Advanced Research Projects Agency (DARPA) initiated the Combat Hybrid Power System (CHPS) program, whose goal is to develop and test a full-scale hybrid electric power system for advanced combat vehicles. To achieve that goal, the program has developed a 100 percent hardware-in-the-loop System Integration Laboratory (SIL)—a reconfigurable laboratory using state-of-the-art hardware and software.

In support of this effort, DARPA requested that the National Research Council (NRC) convene a committee of experts to undertake the following task:

> Address the key issues for emerging technologies in the development of the combat hybrid power system components. The technologies to be addressed include permanent magnet technology for hub motors, Li-ion batteries, and high-temperature, wideband gap materials. Other such emerging technologies may also be addressed.

On August 26 and 27, 2002, the NRC Committee on Assessment of Combat Hybrid Power Systems convened a data-gathering workshop in San Jose, California. The committee targeted the three emerging technology areas specified in the statement of work:

1. Advanced electric motor drives and power electronics,
2. Battery technologies for military electric and hybrid vehicle applications, and
3. High-temperature, wideband gap materials for high-power electrical systems.

In addition, the committee determined that three additional emerging technologies should also be addressed:

4. High-power switching technologies,
5. Capacitor technologies, and
6. Computer simulation for storage system design and integration.

Tables ES-1 through ES-6 summarize the results of the committee's analysis of the technical challenges, performance metrics, and research priorities associated with these six areas.

TABLE ES-1 Advanced Electric Motor Drives and Power Electronics

System/Component	Technical Challenge	Performance Metric	R&D Priorities
Electric motors for traction	Simulation of drive cycles/mission profiles to establish torque-speed requirements of the electrical drive Optimizing auxiliary power unit, battery, and other energy storage device characteristics to meet the torque-speed requirements of the drive Motor and inverter technology development to meet wide constant horsepower speed range without impacting the size of inverters Comparison of various power train configurations, e.g., wheel motors, axle motors with and without gearboxes and transmissions "Apple to apple" comparison of internal permanent magnet motors and inverters with induction and other motors and inverters for traction drive	Changes in component (e.g., motor) design parameters quantitatively linked to changes in overall system performance	Expansion of current research to validate models and link motor design programs with power electronics and drive simulation programs

Materials for electric motors	Electrical losses in copper windings and iron in magnetic materials	Low loss even at high frequencies	Low loss materials that can be readily manufactured in laminar form
	Buried permanent magnet rotors for large machines	Retention of remnant flux density and energy product characteristics	Techniques for injecting magnetic materials into the rotors, and curing and magnetizing them on-site
Power devices and inverters	Inverters that operate with high efficiency at higher power	High-current, high-voltage switching characteristics	Development of wideband gap materials such as SiC
	Improving device cooling		Development of thermal management systems with phase transition and other materials to remove heat quickly from the power devices and inverters and improve transient performance
	Reducing electromagnetic interference (EMI)		Integration of SiC diodes with insulated gate bipolar transistor hard switched inverters to reduce reverse recovery transients to yield low EMI and high efficiency comparable to soft switching inverters
DC bus capacitors	Keeping the voltage ripple within specified limits	Size, efficiency, operating temperature, and ripple current carrying capacity	Fundamental research on materials to meet these requirements
DC/DC converters	High ratio voltage conversion at high power	Performance at high power, EMI/electromagnetic compliance shielding, and packaging size	Design tools for optimizing the combination of devices required and other characteristics, e.g., switching frequency
Integrated thermal management systems	Adequate cooling for both motors and power electronics	Cooling efficiency, packaging size	Development of high thermal conductivity materials such as graphite foams and silicon carbide, in combination with phase transition fluids

TABLE ES-2 Battery Technologies

System/Component	Technical Challenge	Performance Metric	R&D Priorities
Advanced battery concepts	Validation of batteries in vehicle applications	Specific power Specific energy	Triple the power and energy with nanomaterials technology and new chemistries
	Safety		Increased safety (eliminate flammable materials; better packing for isolation, containment, venting; thermally stable materials; diagnostics/ prognostics integrated in pack; eliminate ground fault and arcing; improved materials that reduce gassing)
	Battery management (state of health, state of charge, power availability, life prediction, temperature management, diagnostics, and prognostics)		
Electrode/electrolyte interface	Voltage drop caused by limited chemical reactivity at the interface		Advanced electrode/electrolyte materials with high surface reactivity
			Increased electrode surface area by increased matrix porosity or perhaps application of nanomaterials
Electrolyte	Voltage drop caused by mass transfer overpotential		Electrolytes with high concentrations of reactant species and low ion transfer resistance
Connectors and terminals	Ohmic resistance of materials	Minimized resistance	Low-resistance materials

TABLE ES-3 High-temperature, Wideband Gap (WBG) Materials

System/Component	Technical Challenge	Performance Metric	R&D Priorities
Bulk SiC	Improvement of material quality and substrate diameter	Low defect density	Processing to exploit advantages of 4H-SiC (1120) a-plane crystal orientation
Metal-semiconductor contacts	Improve ohmic contact fabrication processes	Contact stability under extreme conditions	Improvement of science and technology of implantation, implantation activation, and metal-semiconductor metallurgy in wideband gap devices and materials
Device packaging	Development of packaging that can accommodate the high-temperature, high-power characteristics of wideband gap devices while providing high rates of heat removal	Stability, heat removal rate	For SiC devices, development of processes for high-resistivity poly SiC with a matched coefficient of thermal expansion
Bulk GaN and AlN	Improvement of substrate material quality	Low defect density	Fundamental processing research to control defects in bulk GaN and AlN

TABLE ES-4 High-power Switching Technologies

System/Component	Technical Challenge	Performance Metrics	R&D Priorities
Power converters	Higher power densities, switching frequencies, and greater reliability	High power density Manufacturing simplicity Reduced design and verification cycle times	Processes for integration of distributed components with active devices Design tools for three-dimensional thermal management, packaging, system design, and manufacturability
Power electronics for pulse energy storage	Effective decoupling of pulse loads from the power distribution system	High current density High level of decoupling	Development of storage system interfaces with bimodal (slow and fast) power transfer capability Development of interfaces with flexibility to tailor output voltage/current waveforms to requirements of weapons systems
Power distribution network	Mission-critical systems that degrade gracefully under fault conditions	Level of functionality under unplanned faults and component failures	Fundamental understanding of factors affecting system stability Dynamic models of power converter interactions at the DC bus Controls that mitigate instabilities on the DC bus

TABLE ES-5 Capacitor Technologies

Component/System	Technical Challenges	Performance Metrics	R&D Priorities
Polymer film capacitors	Films with improved dielectric properties	Dielectric constant Dielectric withstand	New polymer films with increased dielectric constant and dielectric withstand similar to biaxially oriented polypropylene Filled polymer films: either inorganic filler to improve dielectric strength, high dielectric constant filler to increase dielectric constant, or high dielectric polymer filler to reduce volume within the film, resulting in a combination of increased operating field and increased dielectric constant
Ceramic capacitors	Lack of understanding of aging/failure mechanisms		Research on aging/failure mechanisms under high-temperature, high-field conditions
	Dielectrics with improved properties	Dielectric constant Dielectric withstand	Research to improve high energy density, high-temperature ceramic dielectrics
	Improved operating electric field	Operating field	Ceramic-polymer composites or other technologies that reduce the free volume within the ceramic
Double layer capacitors	Lack of understanding of aging and degradation processes at high temperature		Investigate role of impurities in the carbon electrodes and interactions among the electrodes, electrolyte, and separator
	Improvement of properties of electrolytes, increase in cell voltage, and reduction of equivalent series resistance	Cell voltage equivalent series resistance	
	Predictability of performance over time	Stability of properties	Materials and processes that achieve reproducible cell characteristics that are stable over time, or age uniformly

			over time
	Reduction of current densities	Effective electrode surface area	Research into materials and manufacturing processes that increase the effective surface area of electrodes

TABLE ES-6 Computer Simulation for the Design of Storage Systems and Components

Component/System	Technical Challenges	Performance Metrics	R&D Priorities
CHPSET tool set	Validation against available hardware	Accurate simulation of hardware performance	Validation using data from the Systems Integration Laboratory and possibly hybrid HMMWV and Scout vehicles
Cooling airflow	Modeling cooling effectiveness and cooling airflow, especially through combat grillwork	Resemblance of emulation hardware to notional, demonstrator-level hardware	Emulation of environmental factors Emulation using grillwork hardware
Linkage of CHPSET codes	Effective information transfer between system designers and component designers	Fidelity of vendor-supplied models	Development of a common, expanded solid model database
	Difficulty of modeling hardware provided by vendors	Compatibility of models with CHPSET tools	Vendors encouraged to provide solid models of their hardware, validated at the numeric, component, and system levels
Incorporation of CHPSET tools in a virtual battlefield environment	Understanding of power management during the various modes of operation	Successful integration of a CHPSET model into a higher-level simulation	Integration of CHPSET models into the Joint Modeling and Simulation System (JMASS)
Consideration of environmental factors in CHPSET	Need for realistic mission-related resistance data	Successful incorporation of NATO Reference Mobility Model (NRMM) data into CHPSET	Explore use of NRMM and related software tools such as a route analysis tool kit to generate input data for CHPSET
User options in CHPSET code	Need for comparative analysis capability involving other vehicle options	Executable code user friendliness	Expand executable CHPSET code to include additional user options such as parallel hybrid and conventional vehicles, with appropriate user documentation

Incorporation of CHPSET codes into failure modes and effects analysis (FMEA)	Enhancement of system reliability and mitigation of effect of component failures	Risk priority numbers	Identification of potential failure modes
Design-specific, skid-mounted hardware emulators of Future Combat System	Enhancement of emulator fidelity	Resemblance of emulation hardware to notional, demonstrator-level hardware	Development of design specifics for notional, demonstrator-level systems

1

Background and Overview

INTRODUCTION

The U.S. Army envisions that many of its future combat vehicles will feature a hybrid electric power system containing a diesel or turbine generator that will supply electric power to operate the vehicle subsystems, including electric drive and weapons systems. The hybrid electric power system will enhance the warfighting capability of Army vehicles in many ways, including improved acceleration, stealth capabilities for silent mobility/silent watch, energy weapons for increased lethality, and enhanced armor protection for increased survivability.

Because military requirements for hybrid vehicles (e.g., pulsed power requirements) differ significantly from the requirements for civilian commercial hybrid vehicles, the power system architectures are very different. For example, all military systems currently under study use a series hybrid topology, whereas all civilian vehicles use a parallel hybrid technology. In military hybrids, pulsed power and continuous power must operate together without interference. Pulsed power is required for high-power lasers, an electrothermal chemical (ETC) gun, high-power microwave weapons, electromagnetic armor, and other systems. Elements of the continuous power system include prime power (diesel or turbine), generator, motors, converters, power distribution systems, storage, fault protection, safety systems, and auxiliary power connections (see Figure 1-1).

In 1997, the Defense Advanced Research Projects Agency (DARPA) initiated the Combat Hybrid Power System (CHPS) program, whose goal is to develop and test a full-scale hybrid electric power system for advanced combat vehicles. To achieve that goal, the program has developed a 100 percent hardware-in-the-loop System Integration Laboratory (SIL)—a reconfigurable laboratory using state-of-the-art hardware and software to simulate a 15-ton, six-wheeled Notional Concept Vehicle (NCV) (see Figure 1-2). The Army's proposed specifications for the NCV are shown in Table 1-1.

STATEMENT OF TASK

While some of the technologies required to support combat hybrid vehicle power systems are in hand, many technical challenges remain. Accordingly, DARPA requested that the National Research Council (NRC) convene a committee of experts to undertake the following task:

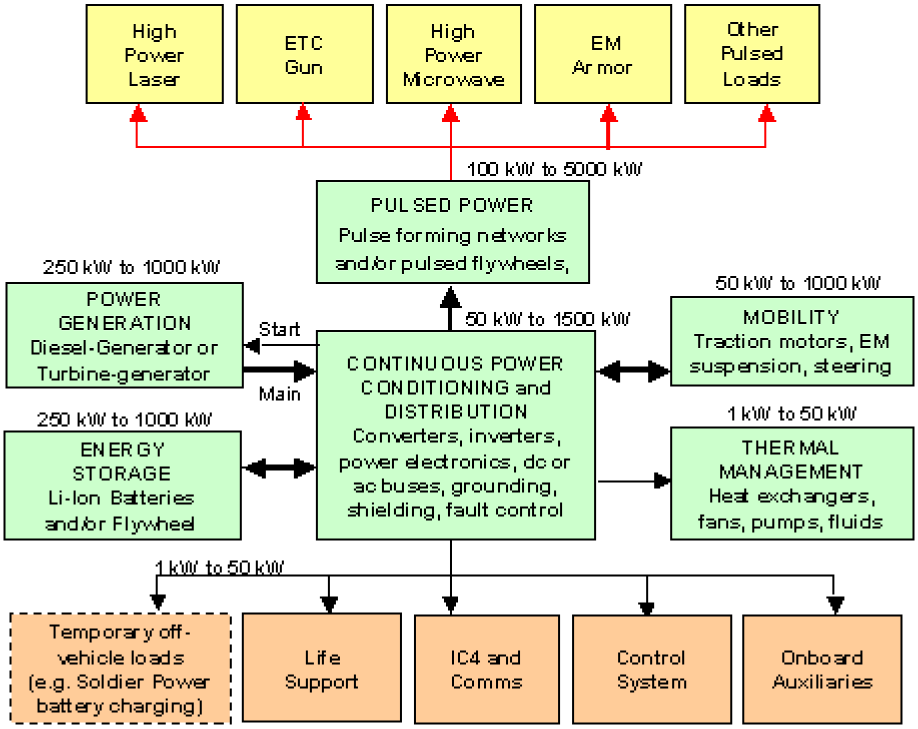

FIGURE 1-1 Basic CHPS/FCS power flow diagram. SOURCE: Courtesy of George Frazier, Science Applications International Corporation.

FIGURE 1-2 One version of the CHPS Notional Concept Vehicle. SOURCE: Courtesy of George Frazier, Science Applications International Corporation.

Address the key issues for emerging technologies in the development of the combat hybrid power system components. The technologies to be addressed include permanent magnet technology for hub motors, Li-ion batteries, and high-temperature, wide band gap materials. Other such emerging technologies may also be addressed.

TABLE 1-1 Notional Specifications for an FCS-like Combat Vehicle Established in 1997

Metric	Measure	NCV Capability
Acceleration	0-60 mph	15 seconds
Gradability	60% slope	6 mph
Tractive effort	Relative to gross vehicle weight	0.7 TE/GVW
Speed	Continuous road speed	70 mph
	Cross-country speed	> 40 mph, 3” rms terrain
Silent/stealth operations	Silent mobility	< 70 dbA @ 20 yards for 20 miles @ 20 mph
Silent/stealth operations	Silent watch	6 hours
Lethality	Energy on target (ground)	3 MJ @ 10 km (3 rpm)
Lethality	Energy on target (air)	150 kJ @ 3 km (1 Hz)
Endurance	Cross-country range	400 miles (30 mph)
Survivability	Armor protection	TOW equivalent ATGM 40 mm AP @ 1000 yards
Environment	Operating temperature extremes	–40 °F to 140 °F

SOURCE: Courtesy of George Frazier, Science Applications International Corporation.

COMMITTEE APPROACH

On August 26 and 27, 2002, the NRC Committee on Assessment of Combat Hybrid Power Systems convened a data-gathering workshop in San Jose, California, in accordance with the statement of work. The agenda for the workshop is shown in Appendix A and the list of participants in Appendix B. The committee targeted the three emerging technology areas specified in the statement of work:

1. Advanced electric motor drives and power electronics,
2. Battery technologies for military electric and hybrid vehicle applications, and
3. High-temperature, wideband gap materials for high-power electrical systems.

In addition, the committee determined that three additional emerging technologies should also be addressed:

4. High-power switching technologies,
5. Capacitor technologies, and
6. Computer simulation for storage system design and integration.

This report, which presents the committee’s analysis of the information gathered in the workshop, devotes a chapter to each of these six emerging technology areas. In each case, the committee attempted to identify the key technical challenges in each area, performance metrics for the technologies, and research priorities for the future.

2

Advanced Electric Motor Drives and Power Electronics

INTRODUCTION

The first step toward development of any hybrid electric powertrain is a detailed analysis of the drive requirements. These requirements include the maximum and continuous operational torque-speed envelopes and the time duration for these operations. A host of vehicle operational modes need to be taken into account to get these requirements. Peak torque is driven by acceleration (0.5g) and tow loads through soft soils. Typical design points for a military vehicle involve a tractive effort-to-gross vehicle weight (TE/GVW) ratio of ~1.1. The continuous torque requirement is determined by load up the steepest gradient (power is determined by the speed up the gradient) and the different drive cycles.

Once these data are available, the next step in the design process is the selection of the right type of drive; this includes the selection of the motor, the gear ratio, and the power electronics. For purposes of discussion, a hypothetical maximum torque-speed envelope is shown in Figure 2-1. The "base" speed is defined as the speed to which maximum torque is required (point A); beyond that, a constant horsepower is required. During the operation with high torque, the torque-to-ampere ratio, also known as torque constant, kt, should be maximized in order to minimize the current handled by the power electronics. This reduces the packaging and cooling of the power electronics and, incidentally, reduces the cost of the drive system also. Generally, this requirement translates into operating the motor with maximum flux until the base speed is reached, followed by flux weakening in the constant horsepower region.

For battery-powered vehicles, it is important to design the drive system to meet the high-speed operating point, because the voltage and the impedance of the motor limit the current and hence the torque produced at high speeds. The proper design of a traction drive system goes beyond optimizing for efficiency over a given drive cycle; in addition, several constraints must be met. A good optimization program incorporating all of these constraints is a necessary tool for this purpose.

Distributed-computer-controlled concepts and systems to integrate the management and control of all the critical elements of the powertrain are also important. The engine, electric motor, transmission, and battery must be coordinated and controlled in an optimal manner at every moment while the vehicle operates. This task can only be accomplished with distributed-computer-control system concepts being developed in current and future hybrid vehicles. This technology is needed to allow completely automatic operation of the powertrain. This chapter does not address such overall system technologies, including continuously variable transmissions, but instead addresses only certain component technologies.

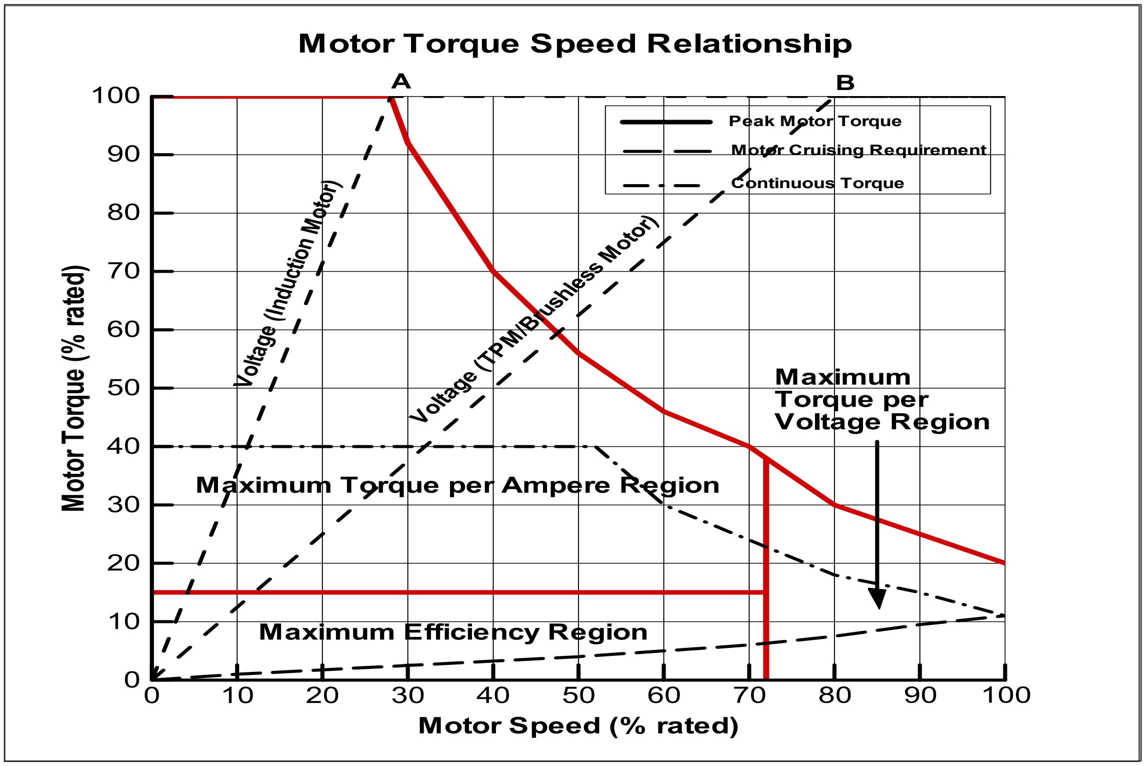

FIGURE 2-1 Motor torque-speed relationship.

ELECTRIC MOTORS FOR TRACTION

There are several electric motors that can be considered for traction:

1. Induction motor,
2. Surface-mounted permanent magnet (PM) motor,
3. Internal PM motor,
4. PM synchronous reluctance motor, and
5. Switched reluctance motor.

Some of these motors are suitable for variable-speed traction drive, and some need to be modified to suit the requirements. For example, for a wide constant horsepower (CHP) region of operation, the induction motor is ideal, but it weighs more and has a lower full-load efficiency than other alternatives. The switched reluctance motor has a similar capability, but suffers some high torque pulsations and noise. Induction motors lend themselves to flux weakening more easily than permanent magnet motors, but they are less efficient than PM motors for full-load operation. For induction motor drives, the maximum voltage point can coincide with the base speed (point A in Figure 2-1), giving the maximum torque per ampere. For internal PM motors, the maximum voltage (point B in Figure 2-1) is closer to the maximum speed point, making the torque per ampere lower than for induction motors.

PM motors have high full-load efficiency and they are lighter, but the flux-weakening region is no more than two times the high torque region. PM motors generally require higher currents to make them adaptable for this application having a wide constant horse power region. Consequently, the inverter must be larger, and cost and packaging become bigger issues. Surface-mounted and axial field PM machines also have excessive iron losses at high speeds, and their part-load efficiency at high speeds is lower. The axial field machines with arigap windings have very low armature reactance and are not suitable for traction drives. They are good for applications having little or no constant horse power region of operation.

PM synchronous reluctance motors with weak permanent magnets that depend on high reluctance torque offer wider CHP range but exhibit larger torque pulsations that are detrimental to the operation of the drive system. Thus, internal PM motors seem to be the most suitable of all the PM machines. In general, PM machines are better suited to multispeed gear boxes similar to automotive transmissions, while induction motors can be operated with a single speed reducer.

Wheel-hub motors have been proposed for military vehicles and they require careful assessment of their impact on ride quality as they increase the unsprung mass of the wheel and lower the wheel-hop natural frequency. PM machines with higher torque/inertia ratio are more suitable for this application. Since they directly drive the wheels one should consider all the performance issues cited above.

To aid research in this area, a tool is needed to quickly design and compare the performance of various motors suitable for a specific application. In other words, given a certain packaging constraint and performance requirements, a tool is needed to give an indication as to which of the motors is most suitable. Current motor design programs rely heavily on empirical experience factors; however, they should be able to link with power electronics and drive simulation programs to determine the performance of the whole system. The results of parameter changes in the motor should be directly quantifiable in terms of the energy consumption over a certain drive cycle for each type of motor. A preliminary effort in this direction has been put in place in the program developed under the Department of Energy contract ADVISOR.[1] More work needs to be done to validate the models and to add the motor design programs to quantify the performance with parameter changes.

MATERIALS FOR ELECTRIC MOTORS

In all electrical machines the majority of losses come from either the copper loss in windings or iron losses in the magnetic materials. Special magnetic materials such as Metglass, which have very low iron loss even at high frequencies, will be ideal for stators

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[1] ADVISOR Web site <http://www.ctts.nrel.gov/analysis/>. Accessed August 27, 2002.

of electrical machines, but these materials are not easy to manufacture into a laminated form. Development of low-loss materials that can be easily manufactured is one of the challenges.

Interior PM motors have an excellent potential to be used in electric traction. Neodium-iron-boron magnets like Magnequench are ideally suitable for motors as they have high enough residual flux density. It is preferable to design these motors with high reactance (1 per unit) to avoid accidental demagnetization due to terminal short circuits. Making these buried PM motors for large machines is a challenge. Techniques of injecting magnetic materials into the motors, and curing and magnetizing them on-site are needed. These materials need to be developed without sacrificing their characteristics of remnant flux density and energy product.

POWER DEVICES AND INVERTERS

The efficiency of power electronics has improved considerably in the last 5 to 10 years and is not much of a concern, particularly for insulated gate bipolar transistor (IGBT) inverters used in electric motors, since they tend to operate at reasonably low switching frequencies so as to limit iron loss in the motors. Further improvement in efficiency can be obtained by the use of wideband gap materials (e.g., SiC; see Chapter 4) for the anti-parallel diodes. SiC diodes used with IGBT power devices in inverters have shown considerable reduction in reverse recovery losses and electromagnetic interference (EMI) comparable to soft switching techniques for motor drives. SiC power devices also offer high-temperature operation and high thermal conductivity but are still in the development stage for high-current, high-voltage application. This is an area of prime research for inverters.

Packaging of power inverters to meet the cooling EMI and electromagnetic compliance (EMC) requirements is also a challenge. The most important development needed in inverters is in the area of packaging and thermal management. There are two levels of cooling requirements to be met: (1) to take heat of the silicon wafer to the substrate on which it is mounted and (2) to take heat from the substrate to the external cooling system. Phase transition liquids and carbon foam materials have excellent promise for meeting these cooling requirements. There is a need for some fundamental research in this area to come up with materials that are most suitable.

BUS CAPACITORS

All variable-speed drive systems require large bus capacitors for exchanging energy between the windings of the motors and the direct current (DC) bus in order to keep the voltage ripple within limits and increase the life of the batteries by limiting the ripple current. The single most common cause of failure in power electronics is the failure of these capacitors. The electrolytic capacitors for this purpose become very bulky and cannot operate at elevated temperatures. Some of the polyfilm capacitors can withstand higher temperature and carry relatively large ripple currents, but they are also bulky. Ceramic capacitors offer the advantages of both smaller size and good high-temperature capabilities, but have complex failure modes that are not well understood. Fundamental work is needed in developing materials for bus capacitors to reduce their size, improve efficiency, operate at higher temperature, and increase ripple current carrying capacity.

DC/DC CONVERTERS

Since a high voltage is produced in the majority of hybrid power systems on vehicles, it becomes imperative to have a DC/DC converter to supply all the auxiliary loads on the vehicle. Although the technology for this is well developed for low-power converters (e.g., a few watts), further work needs to be done for high-power applications. It is a big challenge to meet all of the vehicle standards for EMI and EMC as well as specifications of efficiency and packaging. The soft switching technologies are most suitable to these converters. Since the ratio of voltage conversion is going to be high (e.g., 320:14 V), it is necessary to have a transformer interface and use a combination of devices. Several topologies are possible, and evaluation and development of the optimized converter are a challenge. For example, an IGBT device may be used for the front end and metal oxide semiconductor field effect transistor (MOSFET) in the output. Under this architecture, choice of switching frequency and soft switching become critical.

INTEGRATED THERMAL MANAGEMENT SYSTEMS

Both the electric motors and power electronics need cooling systems in order to operate at their full capacity. Combining the two systems is one of the major challenges. One way to do this is to incorporate the power electronics into the motors with the cooling system made common to both of them. This is a real packaging challenge, but leads to the most desirable solution. New materials such as graphite foam and silicon carbide, which have higher thermal conductivity, need to be developed for this application. Use of these materials, in conjunction with phase transition fluids (vapor to liquid and vice versa), will optimize the performance of the drive systems. Problems of handling these materials need to be addressed, and their physical characteristics (e.g., resistance to corrosion) need to be improved.

SUMMARY

Table 2-1 summarizes the major points of this chapter.

TABLE 2-1 Technical Challenges, Performance Metrics, and Research Priorities Associated with the Application of Electric Propulsion and Power Electronics to Combat Hybrid Power Systems

System/Component	Technical Challenge	Performance Metric	R&D Priorities
Electric motors for traction	Simulation of drive cycles/mission profiles to establish torque-speed requirements of the electrical drive Optimizing auxiliary power unit, battery, and other energy storage device characteristics to meet the torque-speed requirements of the drive Motor and inverter technology development to meet wide constant horsepower speed range without impacting the size of inverters Comparison of various power train configurations, e.g., wheel motors, axle motors with and without gearboxes and transmissions ”Apple to apple” comparison of internal permanent magnet motors and inverters with induction and other motors and inverters for traction drive	Changes in component (e.g., motor) design parameters quantitatively linked to changes in overall system performance	Expansion of current research to validate models and link motor design programs with power electronics and drive simulation programs

Materials for electric motors	Electrical losses in copper windings and iron in magnetic materials	Low loss even at high frequencies	Low loss materials that can be readily manufactured in laminar form
	Buried permanent magnet rotors for large machines	Retention of remnant flux density and energy product characteristics	Techniques for injecting magnetic materials into the rotors, and curing and magnetizing them on-site
Power devices and inverters	Inverters that operate with high efficiency at higher power	High-current, high-voltage switching characteristics	Development of wideband gap materials such as SiC
	Improving device cooling		Development of thermal management systems with phase transition and other materials to remove heat quickly from the power devices and inverters and improve transient performance
	Reducing electromagnetic interference (EMI)		Integration of SiC diodes with insulated gate bipolar transistor hard switched inverters to reduce reverse recovery transients to yield low EMI and high efficiency comparable to soft switching inverters
DC bus capacitors	Keeping the voltage ripple within specified limits	Size, efficiency, operating temperature, and ripple current carrying capacity	Fundamental research on materials to meet these requirements
DC/DC converters	High ratio voltage conversion at high power	Performance at high power, EMI/electromagnetic compliance shielding, and packaging size	Design tools for optimizing the combination of devices required and other characteristics, e.g., switching frequency
Integrated thermal management systems	Adequate cooling for both motors and power electronics	Cooling efficiency, packaging size	Development of high thermal conductivity materials such as graphite foams and silicon carbide, in combination with phase transition fluids

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3

Battery Technologies for Military Hybrid Vehicle Applications

INTRODUCTION

Chemical batteries have been used as electric energy storage devices for many years. With the revival of interest in electric transportation, great effort and investment have been put into the research and development of high-performance chemical batteries. Until recently, however, the battery performance has been far from meeting the requirements of the vehicle application. One of the major problems is the very limited amount of energy stored per unit weight (specific energy). Compared with conventional petroleum and internal-combustion-engine-based systems, far less energy is stored in a practical onboard battery, resulting in limited operation time. This chapter examines the current state-of-the-art of batteries for vehicle propulsion, and promising research areas that could lead to improved performance.

ENERGY DENSITY OF CHEMICAL BATTERIES

The theoretical specific energy density of selected existing batteries is shown in Table 3-1.

TABLE 3-1 Theoretical Specific Energy of Typical Existing Batteries

Reaction	Voltage (V)	Specific Energy (Wh/kg)
Lead acid cell: $PbO_2 + 2H_2SO_4 + Pb \leftrightarrow 2PbSO_4 + 2H_2O$	2.04	170
Edison (Ni-Fe) cell: $Fe + 2NiOOH + 2H_2O \leftrightarrow Fe(OH)_2 + 2Ni(OH)_2$	1.25	260
Ni-Zn cell: $Zn + 2NiOOH + 2H_2O \leftrightarrow Zn(OH)_2 + 2Ni(OH)_2$	1.9	360
Zn-chlorine cell: $Zn + (Cl_2 + 8H_2O) \leftrightarrow ZnCl + 8H_2O$	2.1	410
Al-S cell: $2Al + 3S + 3OH^- \leftrightarrow 2AL(OH)_3 + 3\ HS^-$	1.3	910
Organic lithium: $Li_{(y+x)}C_6 + Li_{(1-(y+x))}CoC \leftrightarrow Li_yC_6 + Li_{(1-y)}CoO_2$		320*

*For maximum value of $x = 0.5$ and $y = 0$.

However, practical batteries have specific energies that are much lower than their theoretical values. This is due to the need for a container, electrode support, connectors, diluted electrolyte, unreacted materials and so on. Table 3-2 shows the data for some existing batteries, and compares them with the mid-term and long-term goals of the U.S. Advanced Battery Consortium (USABC). Lithium-ion batteries have the highest current values of specific energy. These may be designed in a high-power (HP) or high-energy (HE) configuration, depending on the requirements of the load.

TABLE 3-2 Expected Practical Energy Density

		Specific Energy (Wh/kg)				
	Battery	Theoretical	Current	Ratio	Projected	Ratio
Existing	Lead acid	170	40	4.25	50	3.40
	Adision Ni-Fe	260	50	5.20	60	4.33
	Ni-Zn	360	60	6.0	70	5.14
	Zn-Cl	410	70	5.86	80	5.13
	Li-ion high power		85-95			
	Li-ion high energy		135-150			
USABC	Mid-term				80	
Goal	Long-term				200	
Al-based	Al-Fe-O	2,278			455	5.0
	Al-Cu-O	2,198			440	5.0
	Al-Fe-OH	1,903			380	5.0

SPECIFIC POWER CHARACTERISTICS OF CHEMICAL BATTERIES

Specific power is the maximum power per unit battery weight that the battery can deliver in a short period. Theoretically, there is no top limit for specific power. It depends mostly on the manufacturing and material processing technologies. Specific power is also important in the reduction of battery weight, especially for the high power demand applications, such as hybrid electric vehicles. The maximum power that the battery can deliver to the load is limited by the conductor resistance and the internal resistance caused by the chemical reaction. Accurate determination of battery resistance by analysis is difficult. Specific power is usually obtained by measurement.

Table 3-3 shows the status of battery systems potentially available for hybrid vehicles. Although it can be seen that specific energies are higher in advanced batteries, until recently the specific powers showed no such improvement over mature lead acid technology. Li-ion high-power and high-energy batteries with about 4000 W/kg and 600 W/kg, respectively, have been reported.[1] If these results are proven in vehicle tests, they would represent a significant step forward. Work continues on the development of batteries with very high power capabilities of at

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[1] T. Matty. 2002. "Battery Systems for DoD Applications." Briefing presented to the Committee on Assessment of Combat Hybrid Power Systems, National Research Council, San Jose, Calif., August 26.

least 10 to 15 kW/kg, and tests indicate that power levels in excess of 15 kW/kg are possible. New processing techniques are expected to deliver in excess of 30 kW/kg. This will require significant advancement in processing capabilities.[2] The Department of Defense (DoD) has supported and continues to support the development of higher power systems required for future needs—for example, for directed energy systems such as lasers and high-power microwaves. At the same time, the DoD requires lower power density and higher energy density batteries to satisfy the silent watch requirements and stealth operation capabilities.

TABLE 3-3 Status of Battery Systems for Hybrid Vehicles

System	Specific energy (Wh/kg)	Specific power (W/kg)	Energy efficiency (%)	Cycle life	Cost (US$/kWh)
Lead acid	35-50	150-400	>80	500-1000	120-150
Nickel/cadmium	40-60	80-150	75	800	250-350
Nickel iron	50-60	80-150	65	1500-2000	200-400
Nickel zinc	55-75	170-260	70	300	100-300
Nickel/metal/hydride	70-95	200-300	70	750-1200+	200-350
Sodium/sulfur	150-240	230	85	800+	250-450
Lithium/ion/sulfur	100-130	159-250	80	1000+	110
Lithium-ion	80-130	200-300	>95	5000+	200
Li-ion high power	85-95	~4000	>95	—	—
Li-ion high energy	167	~600	>98	—	—

TYPICAL MOBILITY REQUIREMENTS OF MILITARY VEHICLES FOR BATTERIES

Figure 3-1 shows the typical tractive effort and speed of military vehicles under various operational conditions. In order to evaluate the requirements to batteries, these three typical operations are selected: (1) high-speed highway operation, (2) hill-climbing operation, and (3) hard acceleration. The first operation represents the energy demand for continuous operation, and the last operation represents the power demand for intermittent operation. It is assumed that the maximum acceptable ratio of battery weight to total vehicle weight is 0.25. Table 3-4 shows the data of these three operations.

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[2] T. Matty. 2002. “Battery Systems for DoD Applications.” Briefing presented to the Committee on Assessment of Combat Hybrid Power Systems, National Research Council, San Jose, Calif., August 26.

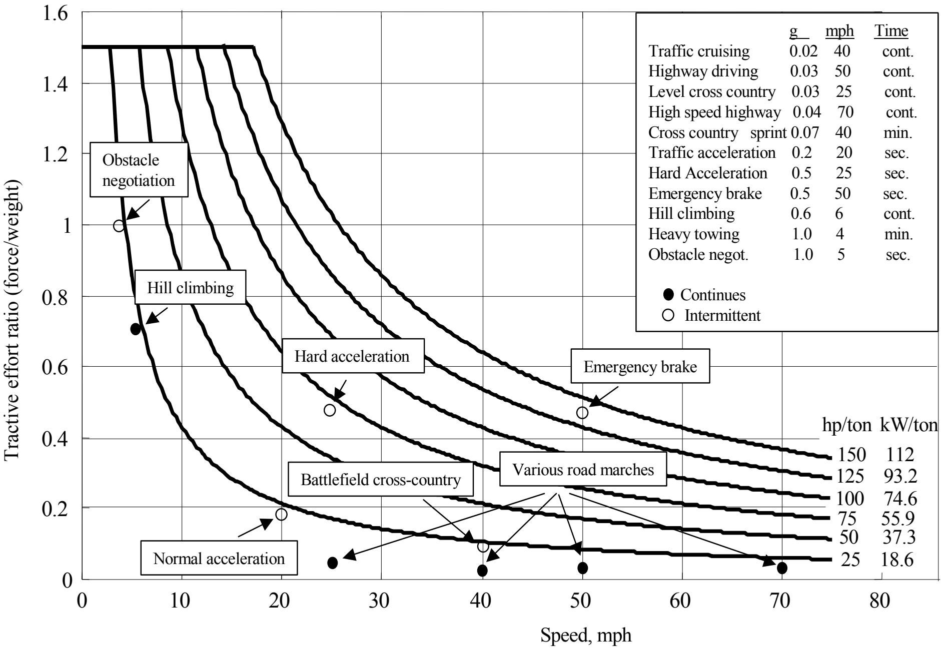

FIGURE 3-1 Power requirement of typical mobility of military vehicles.

Table 3-4. Typical Operations of Military Vehicles

Operation	Speed (mph)	Power (kW/ton) Traction	Battery	Time
High-speed highway	70	12	16	Continous
Hill-climbing	6	16	21	Continous
Hard acceleration	25	54	72	Seconds

When the vehicle demands hard acceleration, sufficient battery power must be supplied. Referring to Table 3-4 and Figures 3-2 and 3-3, this power demand is about 72 kW per ton of vehicle weight. In Figures 3-2 and 3-3, the total weight is defined as the total vehicle weight minus the battery weight. The calculated ratios of battery weight to total vehicle weight for typical batteries are listed in Table 3-5. It is clear that SAFT Li-ion high power and high energy batteries can meet the power demand. Even lead acid batteries may be able to supply sufficient power for hard acceleration.

The driving range performance of the Li-ion batteries is somewhat less satisfactory, however. The maximum driving range on the highway at 70 mph is about 105 miles for the SAFT HE battery and 63 miles for the SAFT HP battery, while the maximum hill-climbing range for the SAFT HE and HP batteries is 6.4 and 4.1 miles, respectively.

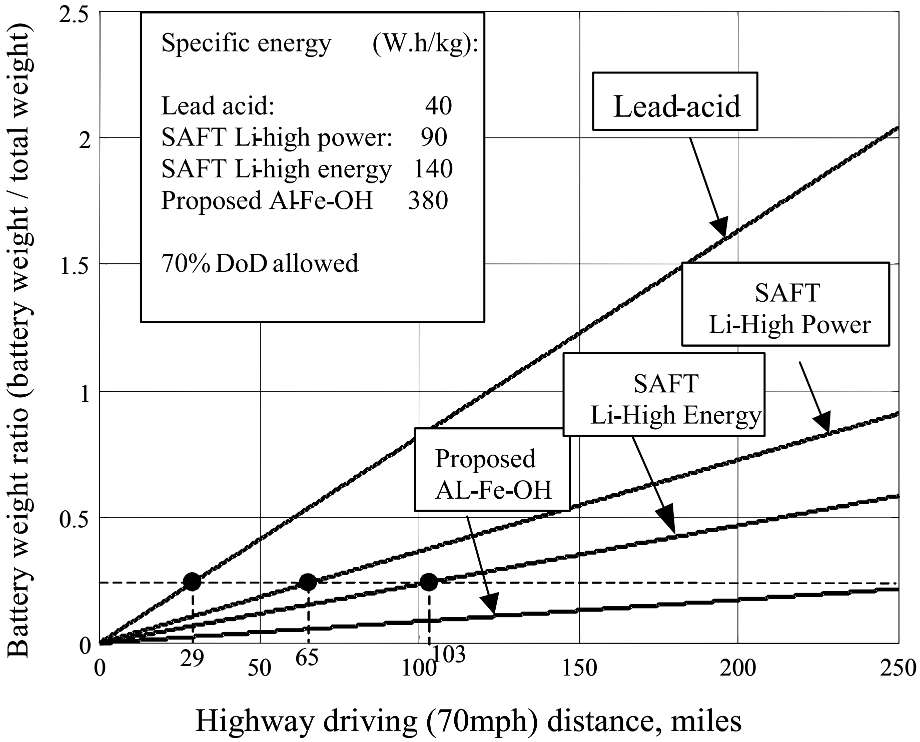

FIGURE 3-2 Battery weight/total weight ratio versus driving range on highway at the speed of 70 mph.

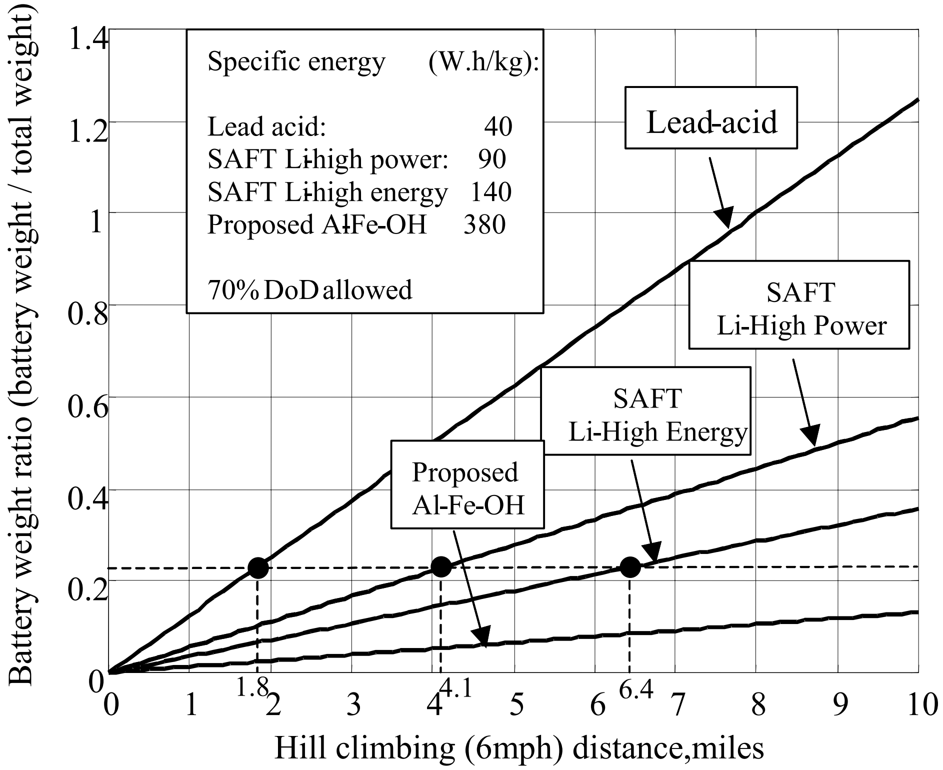

FIGURE 3-3 Battery weight/total weight ratio versus driving range while climbing hill.

TABLE 3-5 Ratio of Battery Weight to Total Vehicle Weight

Battery	Specific Power (W/kg)	Battery Weight/ Vehicle Weight
Lead acid	300	0.24
SAFT Li-high power	3,000	0.024
SAFT Li-high energy	500	0.144
Proposed Al-Fe-OH	—	—

Another battery requirement for military applications is that the fully sealed and water-cooled battery packs can be submerged in 10 feet of water. These batteries should also be intelligently managed with module management and data collection systems. These systems are now being researched by companies in the United States and elsewhere.

BATTERY PERFORMANCE IMPROVEMENT TECHNIQUES

The intrinsic properties of the active electrode materials and electrolyte used determine the cell potential, capacity, and energy density, each of which has a theoretical top limitation. However, battery power capability has no theoretical top limitation. It heavily depends on manufacturing technology to reduce the battery internal resistance, which causes voltage drop on the battery terminals and consequently limits the battery power. The battery voltage drop is generally caused by reaction activity and electrolyte concentration.

The voltage drop caused by the reaction activity may be reduced by two approaches. One is to develop advanced electrode materials and electrolyte that have high chemical reaction activity on the reaction surface. The other approach is to employ electrodes with large surface areas. This will decrease the current density for a given load current and consequently reduce the voltage drop. In addition to simply increasing the geometric size, the electrode area can be dramatically increased by using active materials with high intrinsic surface area, for example, porous matrices.

The voltage drop caused by the electrolyte concentration (sometimes called a mass-transfer overpotential) can be reduced by using high concentrations of reactant species and technologies to reduce the ion transfer resistance. In addition to the voltage drop caused by the chemical reaction, there is also a voltage drop due to the electric ohmic resistance in the connectors and terminals. This can be addressed through the application of low-resistance materials.

The new technologies for improving battery power capability may also include use of nanomaterials, engineered interfaces and surfaces in materials, advanced energy storage and conversion materials, and advanced materials processing and systems manufacturing techniques.

SUMMARY

SAFT high power and high energy Li-ion batteries may be able to meet the power demands of military hybrid vehicles, though their ability to satisfy requirements for vehicle driving range on the highway or up grades appears less certain. Theoretical analysis indicates that hypothetical aluminum-based batteries potentially have high energy density, which is over two times that of the long-term goal of USABC. However, their specific powers are uncertain. Technical challenges and opportunities for improvement in battery performance are summarized in Table 3-6.

TABLE 3-6 Technical Challenges, Performance Metrics, and Research Priorities Associated with the Application of Batteries to Combat Hybrid Power Systems

System/Component	Technical Challenge	Performance Metric	R&D Priorities
Advanced battery concepts	Validation of batteries in vehicle applications	Specific power Specific energy	Triple the power and energy with nanomaterials technology and new chemistries
	Safety Battery management (state of health, state of charge, power availability, life prediction, temperature management, diagnostics, and prognostics)		Increased safety (eliminate flammable materials; better packing for isolation, containment, venting; thermally stable materials; diagnostics/ prognostics integrated in pack; eliminate ground fault and arcing; improved materials that reduce gassing)
Electrode/electrolyte interface	Voltage drop caused by limited chemical reactivity at the interface		Advanced electrode/electrolyte materials with high surface reactivity Increased electrode surface area by increased matrix porosity or perhaps application of nanomaterials
Electrolyte	Voltage drop caused by mass transfer overpotential		Electrolytes with high concentrations of reactant species and low ion transfer resistance
Connectors and terminals	Ohmic resistance of materials	Minimized resistance	Low-resistance materials

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4

High-temperature, Wideband Gap Materials for High-power Electrical Power Conditioning

INTRODUCTION

Electronic devices fabricated from high-temperature, wideband gap (WBG) materials offer a number of advantages over corresponding devices fabricated from silicon. These include higher temperature stability; higher chemical stability in extreme environments; higher thermal conductivity, resulting in reduced cooling requirements; and higher breakdown field, which translates into more compact and higher frequency devices. These characteristics are especially desirable in high-power electronic devices such as those used in the power conditioning systems of hybrid electric vehicles.

Three types of WBG materials are discussed in this chapter: silicon carbide (SiC), gallium nitride (GaN), and aluminum nitride (AlN). Only SiC was discussed during the data-gathering workshop;[1] information on AlN and GaN was obtained from other sources.[2] SiC is a polytype material with different possible arrangements of the Si and C atoms in the lattice. Specifically, the variations of SiC considered were 6H-SiC and 4H-SiC (see below).

The defect density and the effects of specific defects are presently the most telling metrics for WBG materials. In SiC the defect types and effects (micropipe density, screw-thread density, stacking fault density) have been identified, and efforts are under way to circumvent and eliminate them. The standard semiconductor parameters are also metrics for WBG materials. Specifically, the carrier mobilities as a function of applied electric field, the dielectric breakdown strength, the intrinsic resistivity (minimum impurity density), and the thermal conductivity are of importance in comparing and applying the materials in high-power devices.

SILICON CARBIDE

SiC is currently the most practical high-temperature WBG material for advanced power electronics. The large band gap (4H-SiC = 3.26 eV) enables operation with device junction temperatures that can exceed 600ºC. The large band gap also enables a very

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[1] M. Mazzola. 2002. “SiC High-temperature Wideband Gap Materials.” Briefing presented to the Committee on Assessment of Combat Hybrid Power Systems, National Research Council, San Jose, Calif., August 26.

[2] S. DenBaars and U. Mishra, University of California, Santa Barbara, private communications, August 19, 2002.

high breakdown electric field, as illustrated in Figure 4-1. The high breakdown electric field of SiC, which is 10 times greater than that of silicon, translates into thinner conduction regions at constant doping and thus very low specific conduction resistance, as illustrated in Figure 4-2.

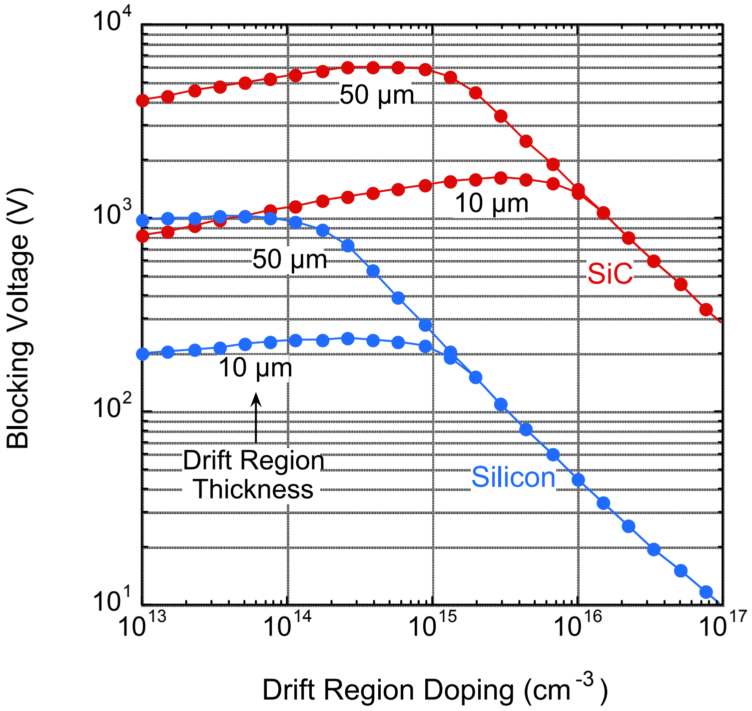
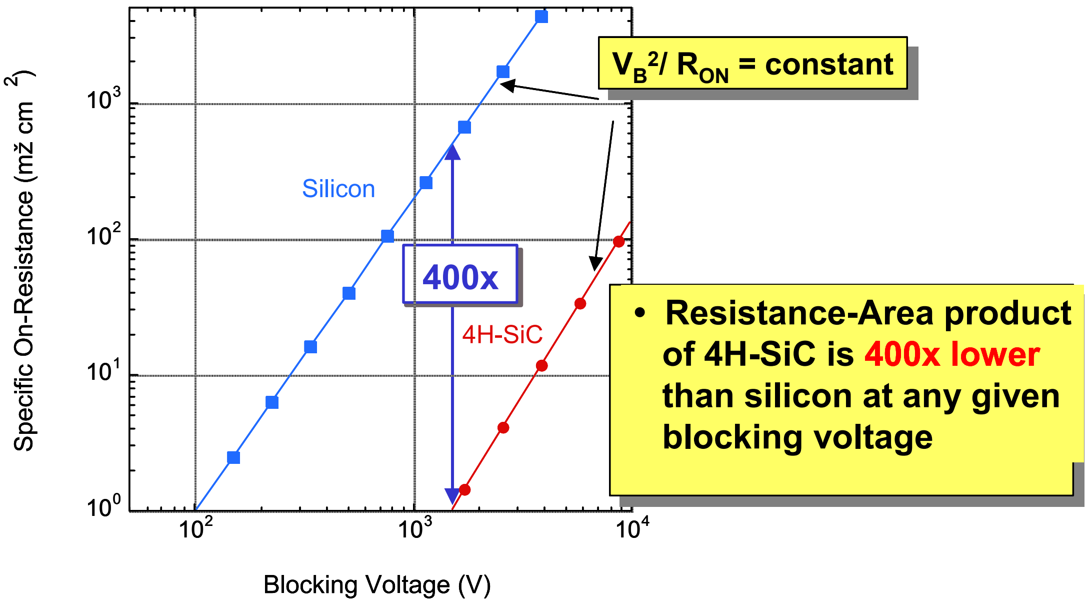


FIGURE 4-1 Comparison of SiC and silicon dielectric strength. SOURCE: Courtesy of Michael Mazzola, Mississippi State University.

Presently, after many years and millions of dollars of government and private investment, high-quality substrates are commercially available. The commercially available substrates, although not sufficiently defect-free for large area device fabrication, permit homoepitaxial layers to be deposited in which high-power devices, which require low-defect materials, can be fabricated. Furthermore, the high thermal conductivity of SiC (4.9 W/cm-K at 300 K) enables increased power density and thus much more compact or much higher power per unit area than silicon devices. Specifically, increased power with SiC is possible when the difference between the junction temperature (T_j) and the ambient temperature (T_a) is small, and passive cooling is possible when the difference between T_j and T_a is large.



V_B^2/ R_{ON} = constant

- **Resistance-Area product of 4H-SiC is 400x lower than silicon at any given blocking voltage**

FIGURE 4-2 Comparison of conduction resistance for SiC and silicon. SOURCE: Courtesy of Michael Mazzola, Mississippi State University.

Furthermore, the chemical resistance of SiC is such that devices can be deployed in challenging environments. Fabrication is facilitated in that, like silicon, the native oxide is SiO_2, which permits normally-off devices based on the metal oxide semiconductor field effect transistor (MOSFET) to be fabricated. However, presently, junction field effect transistors (FETs) are more practical, because defects at the gate insulator-conduction channel interface limit the switching performance of SiC MOSFETs produced for applications.

At present, the world's first commercially available power device based on WBG materials is the SiC Schottky diode (600 V, 4-12 A). In general, the state of the art in SiC devices is operating voltages up to 10 kV and currents up to 100 A, but these parameters have not been demonstrated in the same device. Figure 4-3 illustrates the demonstrated performance of SiC devices.

SiC Crystal Orientations

The crystal orientation in SiC is very important in that it determines the orientation of the micropipes so that the crystal orientation is a metric for the micropipe density. In SiC, there are several options for orienting the surface of the material with respect to the basic crystal orientation. These orientations, illustrated in Figure 4-4, include the "c" plane surfaces and the "a" plane surfaces. The vast majority of previous SiC growth and wafer fabrication efforts have resulted in "c" plane substrates. As

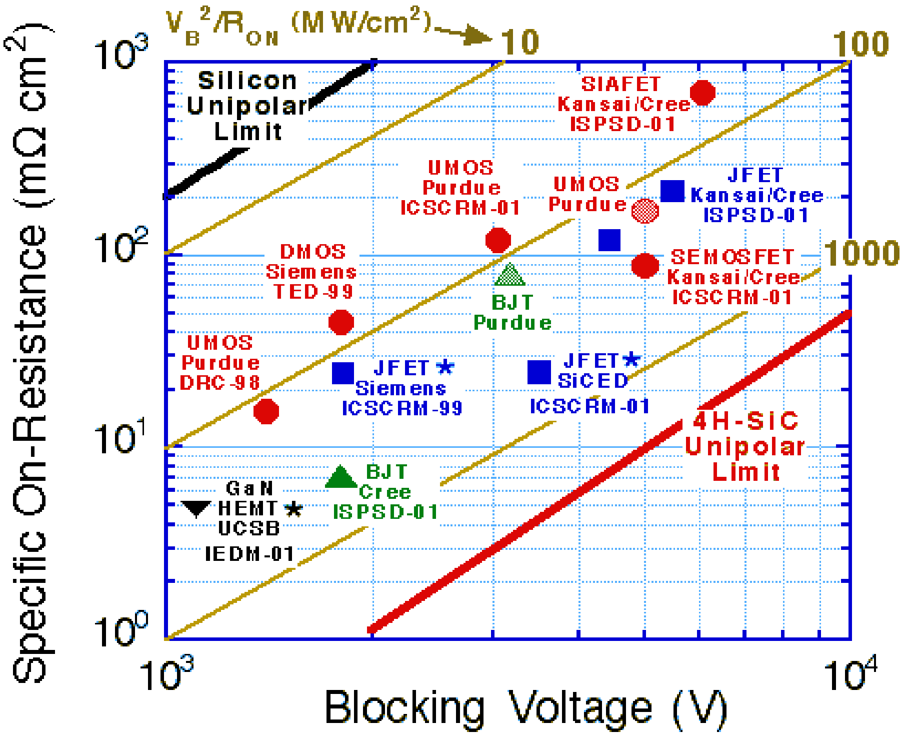


FIGURE 4-3 Comparison of silicon and SiC operating voltage and conduction resistance. SOURCE: Reprinted by permission from J.A. Cooper. 2002. Opportunities and Technical Strategies for Silicon Carbide Device Development. Materials Science Forum 389-393 15-20. Copyright 2002 by Trans Tech Publications, Switzerland.

mentioned previously, the c-plane wafers have micropipe defects that are generally perpendicular to the c-plane wafer surface, and the defect density is sufficiently large to prevent the fabrication of large-area devices. Therefore, the use of low defect density, epitaxial growths on the c-plane wafer surface have been pursued for device fabrication.

Three possible arrangements of Si and C atoms in the lattice (designated 3C, 6H, and 4H), are shown for the (1120) “a” plane in Figure 4-5. The 4H SiC is the polytype of choice for power, because it has the largest band gap of common types, a relatively high mobility, and a small mobility anisotropy. The c-plane is polar (i.e., has a surface with a “carbon face” or a “silicon face,” while the (1120) face is nonpolar, which is important due to the fact that SiC chemical vapor deposition (CVD) epi is sensitive to polarity (especially doping). In addition, c-plane epi growth requires an off-axis cut to ensure polytype replication while the (1120) a-plane does not.

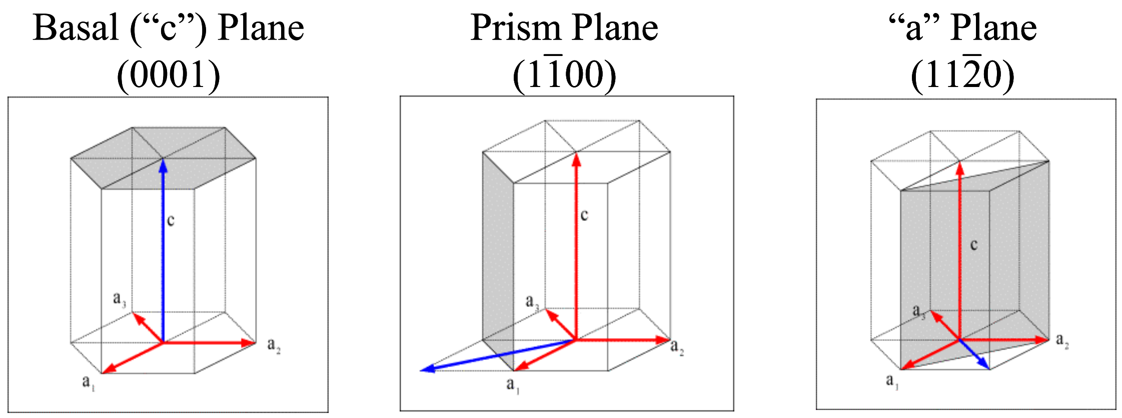


FIGURE 4-4 Silicon carbide crystal and wafer plane orientations. SOURCE: Courtesy of Marek Skorwonski, Carnegie Mellon University. Silicon Carbide Unit Cell. Available at <http://neon.mems.cmu.edu/skowronski/Silicon%20carbide%20unit%20cell.htm>. Accessed August 29, 2002.

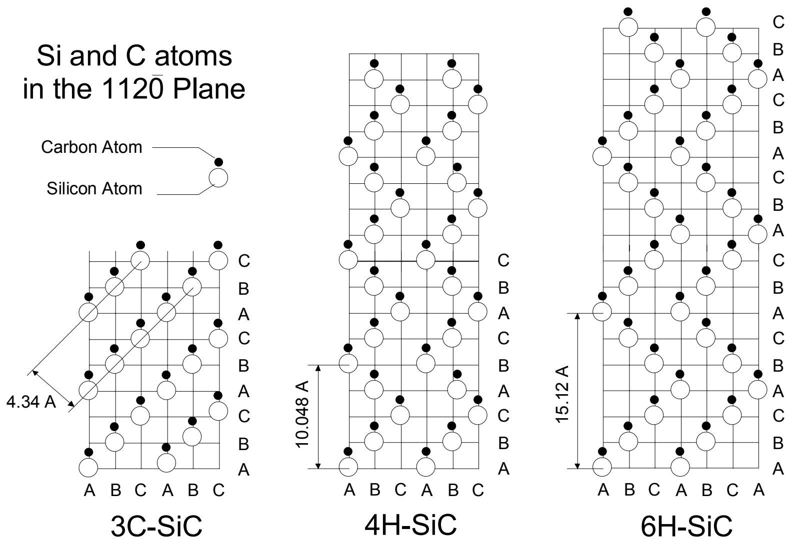


FIGURE 4-5 SiC polytype for (1120) "a" plane. SOURCE: Courtesy of Marek Skorwonski, Carnegie Mellon University. Silicon Carbide Unit Cell. Available at <http://neon.mems.cmu.edu/skowronski/Silicon%20carbide%20unit%20cell.htm>. Accessed August 29, 2002.

The (1120) a-plane material is important in that the direction of micropipe defects are approximately parallel to the surface of the wafer and thus perpendicular to any applied electric field. Furthermore, the micropipes do not propagate into the device-critical epi layer when lying parallel to the surface, which could lead to large-area micropipe-free devices, important for power scaling future devices.

The parameters or metrics that are important in WBG materials such as SiC, GaN, and AlN include lattice mismatch for epitaxial growth, dislocations, interface states, thermal interfaces and thermal resistances, coefficient of thermal expansion, and thermal substrate properties. Note that the lattice mismatch between the base wafer surface and the overlying epitaxial layer is a critical feature for growth of low-defect epitaxial layers.

Current Status of SiC

SiC devices can be divided into two categories: unipolar and bipolar devices. Unipolar devices, such as Schottky diodes, Junction FETs, MOSFETs, and metal semiconductor field effect transistors (MESFETs), exist and work well. The current in single devices is limited by the defect-free wafer area available. Unipolar discrete devices are limited to a few square millimeters in area by the existing materials; current density ratings of 200 A/cm^2 limit device current ratings to ~100 A. To improve performance, micropipe and other material defect densities must decline while substrate diameter increases. Alternative wafer crystal orientations have the potential to greatly increase the area available for device fabrication, and thus they have the potential to scale the device current ratings.

SiC power PiN rectifiers and switches (thyristors, IGBTs, and gate turn offs, or GTOs) will not be commercially available in the near term due in part to the forward conduction instability caused by spontaneously created stacking faults whose origin can be traced to the base material. Again, alternate wafer orientations have the potential to solve the forward conduction instability problem.

MOSFET performance is limited by high channel resistance, which is due to the large interface state densities at the gate insulator–conduction channel interface. Once again, alternative crystal orientations have demonstrated reduced interface defect densities that have the potential to move SiC MOSFETs ahead in this area. Furthermore, bipolar power switching devices such as GTOs and thyristors are currently limited by the complexity of fabrication.

Design trade-offs favor bipolar devices over unipolar around 3 kV. But in addition to the area-scaling problem that limits the current ratings of all SiC power devices (traceable to defects in the substrate), bipolar discrete devices with thick drift regions (required for higher voltages) also suffer dynamic forward voltage instabilities whose origins can also be traced to defects in the substrates. In all cases, the area over which the device can conduct current is limited by the defect density to a few square millimeters.

Improving the Performance of SiC Devices

A critical need for the improvement of the performance of SiC devices is to improve material quality and substrate diameter. An important research priority is to exploit the advantages of the 4H-SiC (1120) a-plane crystal orientation. This material orientation alters the orientation of micropipes and limits their negative effects due to the fact that the micropipe orientation is perpendicular to any applied electric field and current conduction, and because micropipe propagation into device-critical epi layers is eliminated. The (1120) a-plane material has also been shown to reduce defects at the SiC-SiO_2 interface, which makes SiC MOSFETs and IGBTs feasible.

Another need is for improvement in the science and technology of implantation, implantation activation, and metal-semiconductor metallurgy in WBG devices and materials. Special priority should be given to improving ohmic contact fabrication processes. Presently, n-type contacts can be fabricated with $10^{-4}\ \Omega\text{-cm}^2$ to $10^{-6}\ \Omega\text{-cm}^2$; however, contact stability of the preferred nickel-silicide metallurgy requires better science, and better technologies are needed for n-type contacts on subdegenerately doped semiconductors (which are hard to fabricate by implantation).

Fabrication methods for low-resistance p-type contacts for use in bipolar devices, such as GTOs and IGBTs, are well behind that of n-type contacts. The science and technology of dopant implantation and implant activation processes must be improved, since diffusion in SiC is impractical and implantation is necessary for selective doping. Very high temperature annealing is necessary to set deposition.

Energy switching devices, such as those needed in pulsed power weapons systems, have fundamentally different needs that are not optimally met by technology used in conventional continuous power delivery. The high voltages and high peak currents of these applications further stress the existing ohmic contact technology. Solutions beyond conventional methods are required that better integrate the device and package contacting strategy.

Finally, the development of packaging materials and systems to deploy high power density electronic devices is a major—if not the major—obstacle to effectively utilizing the performance advantages of WBG materials in compact high-power systems. SiC is a high-temperature material that can operate at high temperatures, high current densities, and high voltages. Therefore, the package must also accommodate the same parameters while simultaneously providing high rates of heat removal. Fabricating such a package for SiC (in particular) is facilitated because of the wide commercial availability of polycrystalline SiC in several forms for mechanical applications. Specifically, high-resistivity, poly SiC with the same coefficient of thermal expansion (CTE) that can be processed using existing etching techniques is available in large dimensions. The combination of high resistivity and matched CTE in poly SiC makes it an ideal packaging material. The fabrication of the package using poly SiC makes possible the fabrication of microchannel and pin-fin heat exchanger geometries directly in material.

OTHER WIDEBAND GAP, HIGH-POWER ELECTRONIC MATERIALS: GaN AND AlN

Both SiC and GaN materials are superior to the omnipresent silicon because of their larger band gap and the cumulative superiority of a number of other parameters. The larger band gap results in higher bulk material dielectric strength (higher voltage per unit thickness), which in turn leads to more compact and higher frequency devices. In addition, the peak drift velocity of the electrons in GaN can be double that of Si and GaAs (10^7 cm/s) at much higher electric fields. The drift velocity of electrons in SiC continues to rise as the electric field increases above 200 kV/cm, and is also nearly double that of silicon. These characteristics result in a figure of merit that is shown in Table 4-1. The microwave performance for wideband gap materials is also compared in Table 4-2.

TABLE 4-1 Wideband Gap Materials Figure of Merit

Material	Combined Figure of Merit
Silicon	1
GaAs	7.36
6H-SiC	393
4H-SiC	404
GaN	404

SOURCE: Courtesy of M.S. Shur, Rensselaer Polytechnic University, Troy, New York.

TABLE 4-2 Microwave Performance of Wideband Gap Materials

Device	Gate Length (micron)	Power (W/mm)	f_T (GHz)	f_{max} (GHz)
4H-SiC MESFET	0.45	3 @ 1.8 GHz		42
6H-SiC MESFET		2.8 @ 1.8 GHz	16.2	32
SiC SIT	0.5	1.36@ 0.6 GHz		
6H-SiC Lateral JFET	0.3	1.3 @ 0.85 GHz	7.3	9.2
GaN		3.3 @ 1.8 GHz		

SOURCE: Courtesy of M.S. Shur, Rensselaer Polytechnic University, Troy, New York.

Current Status of GaN and AlN

At present there are approximately 50 research groups working on GaN and AlN. The research is focused on electro-optical applications of GaN for high-efficiency light emitting diodes (LEDs), high-temperature FETs, and continuous-wave blue lasers. For example, 15 companies are working on developing a blue laser, but only the Nichia company has a blue laser that can operate for 10,000 hours. The now-common LED traffic signal lights and rear auto tail lights are expanding markets for GaN LEDs, and interior lighting applications are also being pursued. The target for luminous efficiency in an LED is 120 lumens/watt, which can be compared to the luminous efficiency of a fluorescent tube of 80 lumens/watt. Nichia is the current leader in LED efficiencies, with 11 percent for blue, 10 percent for green, and 5 percent for white LEDs.

Another group of R&D efforts are focused on high-power, high-temperature electronics for application in energy-efficient power switching and operation in harsh (high-temperature) environments. For example, NEC is developing a 100 watt continuous-wave, RF (>10 GHz), high electron mobility transistor (HEMT) power amplifier.

Improving the Performance of GaN and AlN Devices

As with SiC, the problems currently being addressed in GaN and AlN materials center on large defect densities and the lack of understanding of their effects. As with SiC, the present approach is to build devices in epitaxial layers. Essentially, a successful or workable GaN substrate technology does not exist. Current surface defect densities are greater than 10^8 cm^{-2}; this is acceptable for LEDs, but not for laser diodes and other devices. The current goal is to reduce the defect density below 10^5 cm^{-2}. The progress in this area is very slow due to the fact that thin film deposition on GaN is very difficult. Metal Organic Chemical Vapor Deposition (MOCVD) systems are currently being used for epitaxial depositions while Molecular Beam Epitaxy (MBE) and Hydride Vapor Phase Epitaxy (HVPE) systems are being developed. Progress in GaN-like materials is also being made using Lateral Epitaxial Overgrowth (LEO), which uses a SiO_2 layer to block surface defects in the epitaxial growth. Two-flow MOCVD epitaxial growth results in the highest-quality epitaxial films.

It appears that the problems related to growing defect-free GaN and AlN materials are limiting the ability to fabricate high-quality devices, and specifically high-power devices that are of interest to the CHPS program. Substrates, and especially low defect density substrates, are currently not available. In fact, except for LEDs, only devices that can be fabricated in an epitaxial layer are available. This situation limits the volume and area of a single device and thus the power-handling capability. Thus, GaN- and AlN-type materials and power devices will not be available within the next five years unless a major breakthrough occurs.

SUMMARY

A summary of the technical challenges and opportunities for improvement of devices based on WBG materials is given in Table 4-3.

TABLE 4-3 Technical Challenges, Performance Metrics, and Research Priorities Associated with the Application of WBG Materials to Combat Hybrid Power Systems

System/Component	Technical Challenge	Performance Metric	R&D Priorities
Bulk SiC	Improvement of material quality and substrate diameter	Low defect density	Processing to exploit advantages of 4H-SiC (1120) a-plane crystal orientation
Metal-semiconductor contacts	Improve ohmic contact fabrication processes	Contact stability under extreme conditions	Improvement of science and technology of implantation, implantation activation, and metal-semiconductor metallurgy in wideband gap devices and materials
Device packaging	Development of packaging that can accommodate the high-temperature, high-power characteristics of wideband gap devices while providing high rates of heat removal	Stability, heat removal rate	For SiC devices, development of processes for high-resistivity poly SiC with a matched coefficient of thermal expansion
Bulk GaN and AlN	Improvement of substrate material quality	Low defect density	Fundamental processing research to control defects in bulk GaN and AlN

5

High-power Switching Technologies

INTRODUCTION

The power distribution network of combat hybrid power systems (CHPS) couples all power electronic systems and other components together, including both continuous and pulsed power systems (see Figure 1-1). This network is mediated by high-power switches that act to limit the interactions among the components. Such interactions can affect the stability and operation of the power delivery platform, hinder fault tolerance strategies, and increase the vulnerability to electrical and magnetic pulses, both from the CHPS's own and from hostile pulsed power systems. Improved reliability of the power distribution network requires that system issues be addressed.

The scope of this evaluation includes the power distribution system and the related power electronics of the CHPS platform. It does not consider the power and high-power switching requirements of specific weapon or defense systems.

Existing switching technologies can meet the electrical demands of CHPS, but there are challenges related to increasing converter power density, decoupling of pulse loads, and developing more fault-tolerant architectures as weapon and defense systems are added.

CONVERTER POWER DENSITY

The highest-priority effort should be focused on increasing the converter power density by increasing switching frequencies and the level of component integration. As power densities increase, thermal issues also become extremely important and vital for reliable systems. The results of such an effort have application well beyond the CHPS platform and have the potential to enhance the competitive position of the national power electronic industry.

Long-term Technology Needs

The long-term technology needs are related to the problems of high-frequency operation, component integration, thermal management, and design tools. An increase in switching frequencies implies reduced size of components such as transformers and filters, which greatly increases the power density. On the other hand, high-frequency switching magnifies the effects of system parasitic losses, which can contribute to component failures.

Component integration contributes to higher power densities and greater reliability. With reduction of connections between components through integration, a major failure mode is reduced. The key components for integration are:

- Filter inductance and capacitance,
- High-frequency transformers,
- Sensors and gate drives, and
- Lowest levels of fast real-time control.

Design tools for three-dimentional thermal management, packaging, system design, and manufacturability are needed to ensure that these issues are integrated in the core design. Currently, such tools are not available at the level necessary to achieve the desired power density.

Performance Metrics

The committee suggests that the most appropriate performance metrics for improved converter technology are these: high power density, a reduction in manufacturing complexity, and a reduction in the length of the device design and verification cycles.

Research Priorities

The committee suggests several research priorites for achieving higher power density converters. These are: developing processes for integrating components (e.g., distributed L and C components with active devices) and integration of high-frequency transformers; developing innovative thermal management techniques for low duty cycle power electronics; and developing an integrated computer-aided design (CAD) tool with mechanical, electromagnetic, and thermal parameter extraction.

POWER ELECTRONICS FOR PULSE ENERGY STORAGE

Pulse energy storage power electronics is an issue uniquely related to CHPS. The nature of pulse power requires that it be buffered from the power platform to prevent major electrical problems. Solutions include flywheel storage with related power electronics or power electronic systems with static storage.

Long-term Technology Needs

There are several long-term issues related to moving power from the Combat Hybrid Power System platform to the weapons systems. Assuming that the weapons systems are pulse power loads, there is a potential that these loads will interfere with the other loads on the electrical platform through voltage drop and/or current surges. Adequate decoupling of pulse loads from the power distribution system is required through the use of high-voltage, high-current switches.

Performance Metrics

The most suitable performance metrics for these switches are high current density and a high level of decoupling.

Research Priorities

Currently, power electronics interfaces with energy storage devices are typically configured to provide for either high or low power flow capability. To increase system flexibility, power electronics interfacing with energy storage devices should be developed to provide bimodal power flow; that is, slow versus fast changes in power transfer. Interfacing systems also need to be developed with flexibility in configuring output voltage/current waveforms to meet the requirements of various weapon systems.

FAULT-TOLERANT ARCHITECTURES

The power distribution network couples all power electronic systems and other components, including such items as generators, storage systems, and traction motors. The interactions among subsystems may cause system performance degradation, or even instability and failures. These interactions also increase the sensitivity of the platform to component failures or damage. Implementation of a DC distribution system with a large number of parallel-connected components requires solving the problem of fast control without reliance on communication. For example, when a load changes its power demand, the energy sources must change their power output to meet the demand without communications.

A power delivery system that depends on a single power component, such as a distribution bus, invites total collapse due to unplanned faults and component failures. Basic platform architectures need to be developed that allow for graceful degradation of mission-critical systems under faults and component failures.

Long-term Technology Needs

A more fundamental understanding is needed of the factors that contribute to—or detract from—the stability of complex hybrid power distribution systems, especially a system that combines continuous and pulse power elements. Particularly vulnerable is the DC bus that provides the backbone of the distribution system. Special efforts to battle-harden the DC bus, such as isolating various sections and providing redundancy for system-critical elements, will be needed to create an architecture with graceful degradation of mission-critical systems under fault conditions.

Performance Metrics

The most appropriate performance metric of fault-tolerant power distribution architectures is the level of functionality that the system displays under unplanned faults and component failures.

Research Priorities

In general, a broader understanding of the factors affecting system stability should lead to design strategies for graceful degradation of systems. More specifically, dynamic models are needed for power converter interactions at the DC bus, as well as the development of controls that mitigate instabilities on the DC bus.

SUMMARY

A summary of the technical challenges and opportunities for improvement of high-power switching technologies is given in Table 5-1.

TABLE 5-1 Technical Challenges, Performance Metrics, and Research Priorities Associated with the Application of High-Power Switching Technologies to Combat Hybrid Power Systems

System/Component	Technical Challenge	Performance Metrics	R&D Priorities
Power converters	Higher power densities, switching frequencies, and greater reliability	High power density Manufacturing simplicity Reduced design and verification cycle times	Processes for integration of distributed components with active devices Design tools for three-dimensional thermal management, packaging, system design, and manufacturability

Power electronics for pulse energy storage	Effective decoupling of pulse loads from the power distribution system	High current density High level of decoupling	Development of storage system interfaces with bimodal (slow and fast) power transfer capability Development of interfaces with flexibility to tailor output voltage/current waveforms to requirements of weapons systems
Power distribution network	Mission-critical systems that degrade gracefully under fault conditions	Level of functionality under unplanned faults and component failures	Fundamental understanding of factors affecting system stability Dynamic models of power converter interactions at the DC bus Controls that mitigate instabilities on the DC bus

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6

Capacitor Technology

INTRODUCTION

A capacitor is defined as a device that stores energy in an electrostatic field. In the early days of electrotechnology, energy storage technologies could be categorized unambiguously as follows:

- Batteries, which store energy in a chemical reaction;
- Capacitors, which store energy in an electrostatic field; and
- Inductors, which store energy in a magnetostatic field.

Recent developments in electrotechnology have blurred these distinctions, especially between batteries and capacitors. There is now something of a continuum between a film capacitor, which truly stores energy in an electrostatic field and can absorb and release energy extremely rapidly, and a true battery (e.g., lead acid), which stores energy in a chemical reaction. For example, a double layer "supercapacitor" might be considered 75 percent capacitor and 25 percent battery, while an Li-ion battery might be considered 25 percent capacitor and 75 percent battery. The present discussion focuses primarily on capacitors that store energy in an electrostatic field.

In the context of combat hybrid power systems (CHPS), where a hybrid electric drive is likely to have substantial stored energy in a high-discharge battery technology such as Li-ion, many of the moderate pulsed loads (e.g., in the 1-kA range to drive diode-pumped lasers) can be supplied directly from an Li-ion battery, assuming that frequent shallow discharges and charges do not impair battery life. Loads such as active armor, electrochemical guns, and so on, which require currents in the 100-kA range, will require high energy density capacitors.

This chapter describes the types of capacitors most relevant to CHPS, their current status, and prospects for improvement of their properties. Promising research avenues for the future are also identified. This chapter does not address inertial energy storage and power production using flywheels (kilowatts to a few megawatts) or pulsed alternators (tens to thousands of megawatts). These inductive energy storage technologies are likely to be a more distant option for pulsed power for some applications.

CAPACITOR TYPES AND CHARACTERISTICS

Polymer Film Capacitors

Organic polymers have a dominant position as the dielectric of choice for high-voltage, microsecond-discharge, high energy density capacitors. Typical organic polymers such as polyethylene (PE) have theoretical band gaps in the range of 8 to 10 eV. However, their effective band gaps are in the range of 1 eV as a result of impurity states near the conduction band. The nature of these impurity states is not clear. Some of them reside at the crystalline-amorphous interface in semicrystalline materials such as PE, but others are associated with impurities introduced during manufacture that can range from oxidation products (e.g., carbonyl groups) to catalyst residues. Thus, the useful band gap of such materials typically ranges from 0.5 eV to 1.5 eV.

The conductivity of polymers is generally greater along the polymer backbone than between polymer chains. Thus, alignment of the backbones (in crystallites) in the plane of the film, as is likely during thin film formation, would result in an anisotropic conductivity with the low conductivity through the film and a higher conductivity in the plane of the film. This very likely explains why capacitor films such as biaxially oriented polypropylene (BOPP) can operate at substantially greater fields than would be suggested by the typical bulk properties.

Polymer film capacitors are often constructed by metallizing the film with evaporated Al, and external connections are made by plasma metal spraying, usually based on a Zn alloy. Electrical connections are soldered to the plasma-sprayed end connections.

Metallized film capacitors have the major advantage of being self-healing, that is, if the film punctures, the nanometer-thick metallization of the film is evaporated in the region of the breakdown, leaving a “clearing spot” that isolates the breakdown region electrically from the remainder of the capacitor. Metallized film capacitors can be designed to operate near the dielectric limits of the film. Clearing failures during operation simply result in gradual loss of capacitance. For energy storage applications, as opposed to tuned circuits, such a gradual loss of capacitance is often an acceptable trade-off for increased energy density.

Ceramic Capacitors

The electronic polarizability of most solids results in a relative dielectric constant of about 2. A few materials, such as ferroelectric and antiferroelectric oxides, have dielectric constants in the range of 10^4; however, this often comes at the expense of substantial temperature and field dependence of the dielectric properties. Advances in materials processing technology have focused on smaller ceramic grain sizes and reduced porosity in the dielectric, which has increased the operating fields to 10 kV/mm. Effective dielectric constants in the range of 1000 with low loss can be achieved in

$(Ba,Sr)TiO_3$ based capacitors with curie temperatures below room temperature. Barium titanate is the most popular dielectric material used for multilayer ceramic capacitors (MLC), but the dielectric constant drops as a function of electric field.

Antiferroelectrics show an increase in the dielectric constant with increase in the bias field due to switching from the antiferroelectric (AFE) to the ferroelectric (FE) phase. The application of an electric field greater than the switching field (E_s) causes a phase transition from the orthorhombic to the tetragonal crystal structure. The AFE/FE property of rare earth doped lead zirconate titanate (PZT) compositions has been exploited to fabricate high energy density capacitors for power electronic inverter applications. Dielectric constants >5000 at a bias field of 5 kV/mm have been observed for proprietary lead lanthanum zirconate stannate titanate (PLZST) compositions.

Ceramic capacitors are made from layers of ceramic material with metallic electrodes applied to the surfaces. Such structures can be arranged to place multiple layers either in series or parallel to increase the voltage withstand or capacitance, respectively. High-voltage capacitors in the range of tens of kV_{dc} are also made from bulk ceramic of substantial thickness and are used in pulsed lasers, and other applications.

HIGH ENERGY DENSITY CAPACITOR STATE OF THE ART

Film/foil capacitors can operate at very high ripple current, but have low energy densities. The best commercial high-voltage capacitors achieve an energy density in the range of 0.6 J/cm^3. This has apparently been extended to about 1 J/cm^3 using modified forms of common capacitors materials such as metallized BOPP and PET film. Other technologies approaching this energy density include soggy foil capacitors with a high dielectric constant polymer coating applied to the nonmetallized side of the foil. Thus, the present state of the art in high-voltage film capacitors appears to be in the range of 1 J/cm^3.

Ceramic capacitors can be efficient at lower voltages, where they can be designed to required voltages below the efficient voltage range of film capacitors. Ceramic capacitors can also operate at very high ripple currents, where metalized film capacitors are limited by the end connections. Greater energy density is the main advantage of nonlinear dielectrics, typically 8 to 15 J/cm^3 for modified PZT as compared to 1 to 2 J/cm^3 for common dielectrics. However, for multilayer ceramic capacitors, there is substantial loss in energy density due to significant electric field derating and packaging. The energy density for a fully packaged AFE/FE capacitor, manufactured by Medronics, is in the 2 J/cm^3 range. In addition, since ceramic capacitors cannot recover from a breakdown in the capacitor structure, they must be designed relatively conservatively.

Double layer "supercapacitors" achieve the largest energy densities presently available in capacitors. However, the operating voltage of such capacitors is limited to a few volts, they do not necessarily operate gracefully in series, and they degrade rapidly at elevated temperatures. Operation at the upper end of the military temperature range is also problematic. Nevertheless, double layer capacitors have a potential role to play as intermediate storage, as they can be charged and discharged much more rapidly than a battery. Also, progress in electrode materials and design is likely to reduce high-temperature degradation and lead to extended life at elevated temperature.

POTENTIAL FOR HIGHER ENERGY DENSITIES

High Dielectric Constant Polymer Film Capacitors

As noted above, self-clearing is essential for high energy density polymer film capacitors, as it allows operation very near the breakdown field of the film. Self-clearing characteristics are a strong function of interfacial pressure within the winding, which is much more uniform in a round winding than in an oval winding. On the other hand, a round winding is volumetrically less efficient when many elements must be combined in series and parallel. Assuming that round windings are required for the reason mentioned above, the volumetric packing efficiency can be no better than $\pi/4$. When end connections and edge margins are included, the packing efficiency is unlikely to be better than 50 percent. Thus, to achieve a packaged energy density of 2 J/cm^3, for example, the winding energy density must be at least 4 J/cm^3. For a film relative dielectric constant of 2.2, this implies an operating field of 640 MV/m, which is roughly the inherent breakdown field of BOPP film. The highest field at which BOPP film can be operated is in the range of 450 MV/m, which would result in a packaged energy density of about 1 J/cm^3, which is roughly the present state of the art.

The only option is some combination of increasing the operating field or increasing the dielectric constant while maintaining the operating field. Data in the literature suggest that the dielectric withstand of BOPP can be increased from the range of 600 MV/m to over 800 MV/m through impregnation with oil. However, such impregnation requires an unreasonable amount of time and would probably make the film impossible to process. More rapid impregnation with a small molecule followed by polymerization or cross linking may be a possibility. If the operating field could be increased by 25 percent, the energy density would increase by about 50 percent, from about 1 J/cm^3 to about 1.5 J/cm^3. If the impregnant were highly polar and raised the dielectric constant, the increase in energy density might be somewhat greater, perhaps as much as 1.75 to 2 J/cm^3.

The other alternative is a high dielectric constant polymer film. PET ("mylar") is widely used as a capacitor film; however, it typically has a lower breakdown and operating field than BOPP. This may be the result of a less advantageous polymer morphology than BOPP, which has a high crystallinity with laminar crystallites aligned in the plane of the film. This puts the electric field across the polymer chains, in the direction of low conductivity and probably accounts for the outstanding dielectric strength of BOPP. If the dielectric strength of PET could be increased to that of BOPP, the energy density would be about 50 percent greater as a result of the larger dielectric constant, which could bring the packaged energy density to the range of 1.5 J/cm^3.

Reaching an energy density of 2.5 J/cm^3 and above will require new materials. One problem with polymer films is that they are expensive to produce in small quantities. Thus, most capacitor films have been byproducts of other, much larger applications. Probably the only film that is now manufactured solely for capacitor use (i.e., where the entire output of a polymer film facility is dedicated to the manufacture of capacitors) is BOPP. As a result, even if a high dielectric constant film with dielectric withstand similar to BOPP were developed, getting it manufactured could be problematic. However, if the relative dielectric constant of capacitor film can be increased to 8, in the range that can be achieved through asymmetric fluorine substitution into appropriate polymers, the required operating stress for an energy density of 2.5 J/cm^3 at 50 percent packing efficiency would be about 375 kV/mm, which is very reasonable for a metallized film capacitor. Dielectric constants in the range of 8 are probably feasible, and if such a film could be developed with the dielectric strength of BOPP, a packaged energy density of about 3.5 J/cm^3 should be possible. Thus, research into such films is worthwhile. Enough is understood of the morphology required for high dielectric strength and the molecular structure required for high dielectric constant that such development would not be purely trial and error.

Films at Higher Operating Fields

As noted above, increasing the operating field brings much more rapid benefits than increasing the dielectric constant, as the energy density is proportional to the dielectric constant but to the square of the field. However, the operating field of polymers is unlikely to be increased substantially beyond that of (possibly impregnated) BOPP, which suggests that metallized film capacitors have the short to medium term potential for packaged energy densities up to about 5 J/cm^3 but probably not much greater. Still, this represents a factor of 5 increase from the present state of the art. The electrical conductivity of all insulators increases at high fields, and the increase nearly always starts in the range of 10 kV/mm. Materials that can withstand very high fields typically do so as a result of two phenomena. One is an immunity to oxidation, so that high field-induced damage is not cumulative. The second is strong interaction between hot electrons and optical phonons, which drains energy from the high energy tail of the electron energy distribution and deposits that energy as heat in the material lattice. Thin films of SiO_2 are an excellent example of a material with both of these advantages. SiO_2 is already oxidized, and optical phonons in SiO_2 interact strongly with hot electrons. The result is a breakdown field in the range of 1500 kV/mm, much higher than that of polymer films. One problem with polymer films is that, being amorphous or semicrystalline, they may not have the medium to long-range order required to support optical phonons.

Nanocomposites One option for addressing this problem is nanocomposites of such inorganic, high field materials as SiO_2 and polymers. Mixing nanoparticles into a liquid is normally very difficult as a result of surface energy considerations that tend to cause the nanoparticles to form strings which increase the viscosity greatly. This can be avoided by growing polymer off the surface of the nanoparticles prior to incorporation through surface-initiated polymerization. Basically, polymer chains initiate at an oxygen at the SiO_2 surface and grow from it. When such compatibilized particles are incorporated into polymers, they look like polymer and do not cause large increases in viscosity, which facilitates mixing. The hope would be that the overlap of the electron wave function of hot electrons in the polymer with the SiO_2 would result in cooling of the electrons as occurs in bulk SiO_2, resulting in a flexible composite with higher dielectric withstand. Past work has indicated than when filler particles become smaller than about 1 μm and are incorporated at a substantial level, the dielectric properties of the composite become similar to those of the filler. This could lead to substantial improvements in dielectric withstand of capacitor films based on presently available polymers. Surface-initiated polymerization from inorganic nanoparticles requires catalysts, which can be difficult to remove after polymerization. Catalyst residue generally degrades electrical properties, such as conductivity, as has been a problem with metalocine catalysts. Thus, the development of high-performance nanocomposites must be considered high risk.

Diamond-like Coatings Increasing the operating field of a capacitor dielectric requires increasing the effective band gap of the dielectric and controlling impurity-induced conductivity. Promising technologies include plasma deposited diamond-like coatings. These coatings must be deposited on a very smooth substrate, such as 2-μm metallized capacitor film. The volume of the diamond-like coatings in which the field resides would only be in the range of 25 to 50 percent of the total volume of the structure, compared to polymer films where the field resides in essentially 100 percent of the volume, as the metallization thickness is negligible compared to the polymer thickness. The other issue is that the deposition rate of such films is presently glacial; however, this can always be overcome with enough capital. Still, such coatings have the potential for higher operating fields, although issues of capacitor structure, self-clearing characteristics, and the operating field actually achievable over large film areas make this technology, at its present early stage of development, a high-risk proposition.

Ceramic Capacitors

Ceramic capacitors are relatively mature. However, as in the case of polymer film capacitors, substantial progress has been made over the last decade. Ceramic capacitors tend to have very high dielectric constant but relatively low dielectric strength as a result of substantial porosity, which is typical of sintered materials. One approach to reducing the free volume associated with sintering is to suspend the high dielectric constant particles in a polymer. This will require good compatibilization of the polymer with the ceramic particles, as can be achieved through surface-initiated polymerization, as discussed above.

Another area in which progress is inevitable is the further development of high dielectric constant, high-temperature, low-loss ceramic capacitor dielectrics. Obviously, a spectrum of such materials with trade-offs among these key parameters is highly desirable.

Ceramic capacitor technology would undoubtedly benefit from funding for investigations of high-temperature, high-stress failure mechanisms. These may be the result of ion migration and other processes but are not yet well understood. Understanding of high-temperature, high-stress failure mechanisms would clearly benefit, or perhaps should be a prerequisite to the development of, new materials.

Double Layer Capacitors

Double layer capacitors are energy storage devices that convert chemical into electrical energy and are particularly suited to providing the energy to power electrical devices. These capacitors have two electrodes separated by a separator having an ionically conductive electrolyte, but their energy can be composed of double layer capacitance. They are rechargeable devices designed to have a very high cycle life. Like conventional capacitors, double layer capacitors have higher power and lower energy than rechargeable batteries.

Double layer capacitors are at a much earlier stage of development than are film capacitors. As a result, progress is more easily predictable. At present, aqueous electrolytes provide voltage drops per electrode a little over 1 V with relatively low equivalent series resistance (ESR). Organic electrolytes can operate at over 3 V, but have much greater ESR. Clearly, a combination of greater voltage per electrode combined with low ESR is highly desirable, and work to define the fundamental limits of electrolyte technology in this context would probably contribute toward progress.

Consistency is another issue. Double layer capacitors have relatively poor high-temperature aging characteristics, which may be related to impurities in the carbon electrode and/or temperature-dependent leakage current. The nature of impurities that are detrimental to long-term, high-temperature operation needs to be determined, as does any basic relationship between leakage current and capacitor life.

Double layer capacitors have complex dielectric time constants related to the pore structure of the carbon electrode. Present pore structure reduces the effective electrode surface area to substantially below the theoretical value. Thus, research into the carbon electrode is likely to result in progress on a large number of fronts, including high-temperature aging, volumetric efficiency, and dielectric performance.

For double layer capacitors to reach their full promise, capacitors must be manufactured with well-defined, stable operating characteristics, in terms of dielectric time constants, long-term and high-temperature degradation, and so on, so that large numbers of double layer capacitors can be operated in series over long periods of time through a wide range of charge-discharge cycles without the need for complex voltage balancing circuitry. This will require substantial improvements in materials and uniformity of materials. At this point in time, the relevant materials parameters are not understood, let alone the means by which the quality of these parameters might be controlled. Thus, the first step is to undertake research to quantify the relevant materials parameters. The improved understanding resulting from such work is likely to have payoffs well beyond the short-term need to improve product quality and uniformity.

SUMMARY

The present state of the art in microsecond discharge, high energy density capacitors appears to be about 1 J/cm^3 (packaged) based on improved polypropylene dielectric. From the preceding discussion, and acknowledging that technology forecasting is extremely risky, the limits to microsecond polymer film capacitor technology appear to be in the range of 5 J/cm^3 based on the use of yet-to-be-developed high dielectric constant films at operating fields typical of BOPP. Moving beyond 5 J/cm^3 would require operating at substantially increased fields and would require a fundamental improvement in dielectric technology, such as a nanocomposite or diamond-like coating dielectric, which has yet to be developed.

Thus, short to medium term, high energy density can be pursued through the development of improved high dielectric constant polymer films and the technology to manufacture them in modest quantities, at least on a prototype basis, such as vacuum polymer deposition. For the longer term, dielectrics with the potential for increased operating field should be pursued, such as diamond-like coatings and nanocomposites.

Ceramic capacitor technology will almost certainly be important for power converters with a hybrid electric vehicle, for which filters make a significant contribution to mass and volume. As well, the upper operating temperature of such capacitors will be very important. Thus, research to improve the energy density and operating temperature range of ceramic capacitors should have a definite payoff to CHPS.

The relevance of double layer capacitors to CHPS is less clear and will depend on the capability of the battery to deliver large, short-term currents, undergo frequent, shallow charge-discharge cycles, and so on. Technical constraints may favor the inclusion of a double layer capacitor bank as a buffer that is more capable of rapid charge–discharge cycles.

A summary of the technical challenges and opportunities for improvement of high energy density capacitors is given in Table 6-1.

TABLE 6-1 Technical Challenges, Performance Metrics, and Research Priorities Associated with High Energy Density Capacitors

Component/System	Technical Challenges	Performance Metrics	R&D Priorities
Polymer film capacitors	Films with improved dielectric properties	Dielectric constant Dielectric withstand	New polymer films with increased dielectric constant and dielectric withstand similar to biaxially oriented polypropylene Filled polymer films: either inorganic filler to improve dielectric strength, high dielectric constant filler to increase dielectric constant, or high dielectric polymer filler to reduce volume within the film, resulting in a combination of increased operating field and increased dielectric constant
Ceramic capacitors	Lack of understanding of aging/failure mechanisms		Research on aging/failure mechanisms under high-temperature, high-field conditions
	Dielectrics with improved properties	Dielectric constant Dielectric withstand	Research to improve high energy density, high-temperature ceramic dielectrics
	Improved operating electric field	Operating field	Ceramic-polymer composites or other technologies that reduce the free volume within the ceramic
Double layer capacitors	Lack of understanding of aging and degradation processes at high temperature		Investigate role of impurities in the carbon electrodes and interactions among the electrodes, electrolyte, and separator
	Improvement of properties of electrolytes, increase in cell voltage, and reduction of equivalent series resistance	Cell voltage equivalent series resistance	
	Predictability of performance over time	Stability of properties	Materials and processes that achieve reproducible cell characteristics that are stable

			over time, or age uniformly over time
	Reduction of current densities	Effective electrode surface area	Research into materials and manufacturing processes that increase the effective surface area of electrodes

7

Computer Simulation for Storage Systems Design and Integration

INTRODUCTION

Hybrid vehicles, even ones without the additional electric loads of a combat vehicle, represent complex systems for which computer simulation is manifestly the best means of sizing the various components. This is particularly true when evaluating trade-offs among various means of storing energy, such as batteries and flywheels. Component sizes are readily varied in software, but they are varied at great cost in time and money when in hardware. Computer simulation and modeling are also the norm when engineering individual components of a hybrid system such as power converters or pulse-forming networks for weapons systems.

It is equally manifest, for such complex systems, that simulation and modeling must be verified through hardware emulation. The CHPS program recognized the importance of both activities when it pursued the dual avenues of software simulation via the "CHPSET" code set and hardware emulation via the Systems Integration Laboratory (SIL); (see Chapter 1).

CHPSET contains a hierarchy of codes, from a broad-brush system representation useful for size/weight trade-off studies, to a detailed electrical circuit model for designing individual electrical components. The set includes purpose-written codes, commercial software, and a mission database. Table 7-1 outlines CHPSET.

TABLE 7-1 Description of CHPSET Components

Tool	Description
CHPSPERF	Performance modeling in MATLAB/Simulink, Saber, and other environments
CHPSIZE	Sizing and packaging methodology code written in Visual Basic
CHPSEMI	High-frequency modeling of EMI environment
VITMAC	SAIC-developed multi-physics code for steady-state and transient thermal-fluid response with companion FEA codes
Pro/ENGINEER	Commercial three-dimensional solids modeling code for rendering and packaging
Operational profiles	Mission profiles and vignettes

Table 7-2 outlines some vehicle components now or previously incorporated into SIL.

TABLE 7-2 Hybrid Vehicle Hardware Components Incorporated into the Systems Integration Laboratory

Component	Description
Engine/generator	Caterpillar 3126B engine with induction generator 750VDC, 280 kW
Traction motors	750 VDC, 100 kW continuous, 300 kW intermittent
Battery	Nickel cadmium, 300 to 900 VDC (reconfigurable), 50 kWh
Battery	Li-ion, 530 VDC, 30 kWh
Flywheel/generator	750 VDC, 2 kWh, 160 kW
Pulse power	100 kJ, 10 KV ETC pulse-forming network and power supply
Cooling system	Full vehicle emulated cooling system
Control system	Fully computerized, distributed system capable of running mission scripts autonomously

SIMULATION AND MODELING NEEDS

Simulation and modeling stand somewhat apart from the committee's other workshop topics, which focus on hardware and technologies. Focusing on a particular software set (CHPSET) tended to narrow the scope of the discussions, as may be seen from the following list of discussion topics:

1. The necessity that CHPSET be validated using SIL, and possibly data from the hybrid HMMWV and Scout vehicles;

2. The difficulty of modeling cooling airflow, particularly through combat grillwork, and the necessity that this flow be emulated in hardware;

3. Linkage of the CHPSET codes in order to automate the design process;

4. Incorporation of appropriate CHPSET tools into a virtual battlefield environment to allow interactive mission development;

5. Expanded consideration of environmental factors (heat, cold, rain, mud, terrain roughness, and so on), given that they affect such factors as tractive effort, battery performance, and turbine performance;

6. Inclusion of more user options (such as modeling parallel hybrid systems, and conventional vehicles) in the executable version of CHPSET;

7. User documentation to accompany the executable package;

8. Incorporation of CHPSET into failure modes and effects analysis (FMEA); and

9. Construction of design-specific, skid-mounted emulators for use in verification and testing of future combat system (FCS) hardware.

In this list, items 1, 2, 6, 7, and 9 are highly specific and may stand as recommendations without further comment.

With respect to linkage of the CHPSET codes (item 3), the committee offers the following "vision" of how such linkages might be implemented. Modeling and simulation of vehicle systems require both a solid modeler and a system simulator, and these need to be linked and consistent. By embedding performance simulations in the solid model components, creation of a solid model could automatically create a performance simulation usable for examining the vehicle's electrical, thermal, and automotive performance.

Because hybrid power systems by their nature involve multiple disciplines, the information needed will have to come from areas with which the user is not necessarily conversant. A common expanded solid model database is one method to control and transfer information between system designers and component designers that can be both accurate and timely, resulting in better vehicle simulation configuration control.

The source of the information in the database is different depending on whether the system is being used in a forward-looking design study or in a fieldable system design. In the first case, the system should know enough about the components to generate the information required for the simulation. For example, the designer should be able to say he or she wants a 100-kW, PM motor that is 0.30 m in diameter and 0.20 m long and have the simulation (1) give an indication of the technical feasibility of the machine and (2) generate generic resistances, inductances, and so on, necessary to model the machine. The user should be able to override this information, should better information be available.

Where there are existing pieces of hardware from a vendor, the vendor should provide a solid model of this hardware that can be dropped in the solid model and a "black-box" mathematical model that describes that piece of hardware and its interfaces (electrical, mechanical and software) to the outside world. This technology is available and being used in other applications. Vendors routinely provide either two-dimensional or three-dimensional mechanical models with mass properties of their hardware. Electrical component vendors routinely supply both datasheets and circuit simulation (e.g., SPICE) models of the electrical properties of their hardware. With a standard interface that fully describes the frequency and fidelity of the models, it is conceivable that they could provide "digital" datasheets describing the electrical, mechanical, and thermal interfaces of their hardware for use in combat vehicle simulations.

Model validation is critical if the modeling and simulation system is to be widely used and disseminated. Model validation needs to be performed at three different levels:

1. *The numerics level*. The simulation must be based on robust numerical procedures and processes that are well documented at the limits of applicability.

2. *The component level*. This can and should be handled at the vendor level when there are specific pieces of hardware. If vendors will be supplying "black-box" models, then they will also be responsible for ensuring that the models they supply faithfully replicate their machines.

3. *The system level of validation*. For CHPS, validation at this level must make use of the System Integration Lab, skid-mounted emulators (as noted in item 9, above) and fielded hardware to ensure that the models operate as expected.

Discussion item 4, above, addresses the potential for using CHPS vehicle simulators to assist in establishing an understanding of how best to use the vehicle during the various modes of operation with power management as the principal consideration. For example, overusing a weapon system during a short duration of time could create a situation in which the vehicle would not have enough power reserves to overcome the resistance forces associated with maneuvering over challenging terrain in the remainder of the projected mission path. Vehicle-level simulators exist for training soldiers how to effectively operate specific vehicle systems, such as the HMMWV ("Hummer"), Bradley Fighting Vehicle, and M1 Abrams Main Battle Tank. Generic vehicle-level simulators such as the Close Combat Tactical Trainer (CCTT) exist as well. CCTT can be set up and programmed to approximate most known and future vehicles in both peacetime missions and realistic combat scenarios. The total energy balance, including drive systems, weapons systems, and other energy needs, is a critical issue for these vehicles. Greater emphasis should be placed on the importance of this type of simulation for hybrid vehicles and comparison with standard vehicles and standard weapons systems. This information will be vital in understanding options and making trade-offs in design.

In integrating CHPSET models into a higher-level simulation, the committee believes that consideration should be given to the Joint Modeling and Simulation System (JMASS). JMASS is a standard engineering/engagement-level simulation support environment that allows modelers to build, configure, assemble, execute, and process representations of real-world systems into simulations. The Army recognizes the potential benefits of this standard system and has made a commitment to support its development and adopt it for use to support evolving and future Army modeling and simulation (M&S) requirements. Quoting from a recent paper[1]:

> This engagement/engineering level M&S system breaks new ground in the realm of Object-Oriented (OO) digital constructive simulation. While other M&S systems deliver a complete, integrated simulation as their end product, JMASS instead provides an architecture, interface standards and a set of GUI-based tools, which can be used to build models to those standards and integrate these models with the architecture components to in turn build simulations. While other

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[1] Meyer, Robert J. ASC/AAJ. 2000. Joint Modeling and Simulation System (JMASS), What it Does .... and What it Doesn't. (JMASS JPO). Online. Wright Patterson AFB. Available at http://www.redstone.army.mil/amrdec/jmass/library/JMASS_SIW_Paper.doc. Accessed December 2002.

> M&S systems have their evaluation mechanisms embedded and for the most part pre-determined, JMASS forces applications to define those mechanisms in re-usable, re-configurable components. This challenges potential users to thoroughly understand and decompose their problems and at the same time offers them extraordinary flexibility in implementing solutions to those problems. While other M&S systems leave interfaces as an "exercise for the reader," JMASS uses powerful code-generation techniques to lock-in those interfaces, virtually assuring code reliability and stability.

Discussion item 5, above, consideration of environmental factors, arose from lengthy discussions of the NATO Reference Mobility Model (NRMM) as a well-validated, widely used model of the road/vehicle interface. The resistance forces that CHPS vehicles encounter will drastically vary depending on the mission. Realistic mission-related considerations need to be applied when defining the resistance force input data for CHPSET. NRMM and other related software tools, such as a route analysis tool kit, could provide the realistic mission-related resistance data required for CHPSET.

NRMM is a comprehensive analytical model designed to objectively evaluate the on- and off-road mobility of ground-based vehicles. It uses physics-based algorithms with vehicle-terrain interaction relationships that are primarily empirical. NRMM predicts go/no-go and speed as basic outputs based on input data that include detailed characterizations of the vehicle and terrain, considerations of weather and seasonal effects, and considerations of other speed limiting constraints related to human factors and powertrain-independent vehicle characteristics. NRMM is typically used to analyze the mission-related performance of wheeled and tracked vehicles for operations in realistic theaters of operation that can cover vast areas of terrain.

The most commonly used mission consideration is based on predicting an effective mission speed, referred to as the Mission Rating Speed (MRS). For the MRS, it is assumed that the vehicle may have to operate on any terrain unit in the theater of operation based on a predefined mix of primary roads, secondary roads, trails, and cross-country terrain that make up the vehicle's mission profile. The mission profile is typically defined in the Operational Requirements Document for the vehicle. The MRS is essentially a wide-area, statistical measure of a vehicle's maneuver effectiveness considering the total theater of operation. Other mission considerations have recently been made possible by the development of a route analysis tool kit. With the tool kit, realistic mission plans can be developed by laying out routes of operation on standard Defense mapping assets as illustrated in Figure 7-1. This technique provides for a more realistic measure of mission effectiveness and does not rely on a predefined mission profile.

NRMM predicts speed using the powertrain-dependent maximum tractive force versus speed curve, the maximum tractive force available from the terrain, the speed-reducing slip that will occur on the terrain, the motion resistance forces acting on the vehicle, and other powertrain-independent speed limiters, as illustrated in Figure 7-2. The model predicts the basic components used to determine these five major items for the vehicle in each of the many discrete terrain units (typically 100-meter by 100-meter) that make up

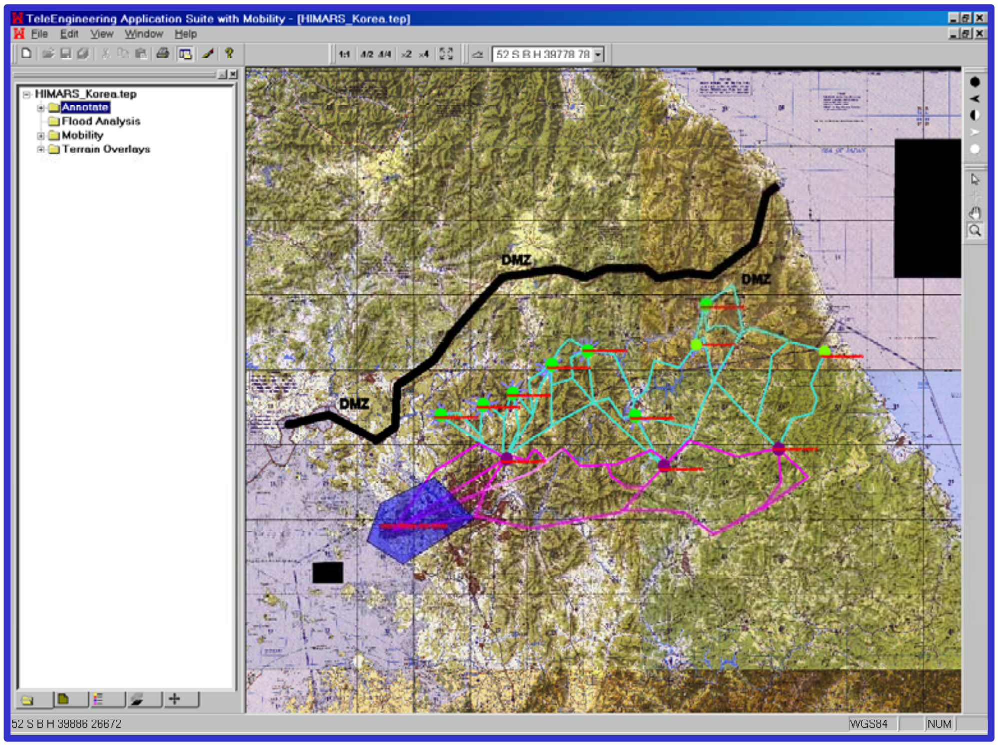

Figure 1. Mission plan for NRMM predictions using a route analysis tool kit
Courtesy of Jody Priddy, U.S. Army Engineer R&D Center (ERDC).

the entire theater of operation for the mission. The resistance forces that are considered in NRMM include rolling resistance on pavement and in soil of varying type and strength, resistance due to climbing slopes, vegetation (i.e., tree) override resistance, obstacle override resistance, and resistance from traversing curves on roads and trails.

For typical applications of NRMM, the basic components of the five major items, such as the magnitude of the various resistance forces, are not catalogued for output. However, for special applications, the basic prediction components can be catalogued. For example, the resistance forces from the various sources associated with each terrain unit can be catalogued for output. This would allow output of resistance force versus distance (or time) tabulations for the vehicle operating in the mission-related theater of operation. This special application was demonstrated in a recent study in which ERDC used NRMM to assist the U.S. Marine Corps and the Defense Advanced Research Projects Agency in the design phase of the Reconnaissance Surveillance Targeting Vehicle (RSTV), which has in-hub electric drive.

In this effort, NRMM was used to characterize the power required to overcome the mission-related resistance forces acting on the RSTV. Various operating theaters and seasonal scenarios were used in the study to relate the effective mission resistance and associated power requirements for several mission concepts. In addition, ERDC developed a special technique for determining a resistance force associated with terrain roughness. Terrain roughness is handled in NRMM as a human factors speed limit, but there would be an effective resistance force associated with traversing rough terrain. This additional resistance force is needed for the special application of using NRMM to define power requirements for CHPS vehicles.

SUMMARY

A summary of the technical challenges and opportunities discussed above for improvement of computer simulation for the design of storage systems and components is given in Table 7-3.

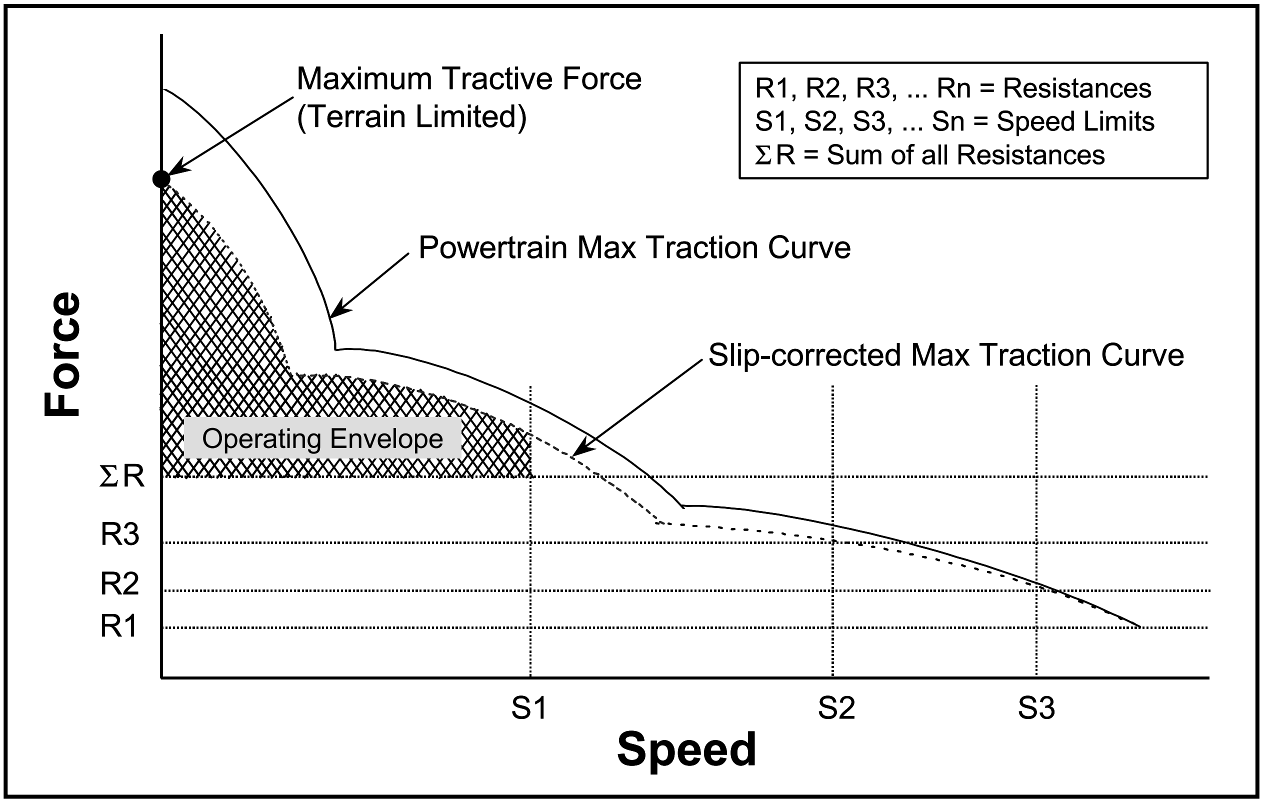

FIGURE 7-2 NRMM basic speed prediction methodology. SOURCE: Courtesy of Jody Priddy, U.S. Army Engineer R&D Center.

TABLE 7-3 Technical Challenges, Performance Metrics, and Research Priorities Associated with Computer Simulation for the Design of Storage Systems and Components

Component/System	Technical Challenges	Performance Metrics	R&D Priorities
CHPSET tool set	Validation against available hardware	Accurate simulation of hardware performance	Validation using data from the Systems Integration Laboratory and possibly hybrid HMMWV and Scout vehicles
Cooling airflow	Modeling cooling effectiveness and cooling airflow, especially through combat grillwork	Resemblance of emulation hardware to notional, demonstrator-level hardware	Emulation of environmental factors Emulation using grillwork hardware
Linkage of CHPSET codes	Effective information transfer between system designers and component designers	Fidelity of vendor-supplied models	Development of a common, expanded solid model database
	Difficulty of modeling hardware provided by vendors	Compatibility of models with CHPSET tools	Vendors encouraged to provide solid models of their hardware, validated at the numeric, component, and system levels
Incorporation of CHPSET tools in a virtual battlefield environment	Understanding of power management during the various modes of operation	Successful integration of a CHPSET model into a higher-level simulation	Integration of CHPSET models into the Joint Modeling and Simulation System (JMASS)
Consideration of environmental factors in CHPSET	Need for realistic mission-related resistance data	Successful incorporation of NATO Reference Mobility Model (NRMM) data into CHPSET	Explore use of NRMM and related software tools such as a route analysis tool kit to generate input data for CHPSET
User options in CHPSET code	Need for comparative analysis capability involving other vehicle options	Executable code user friendliness	Expand executable CHPSET code to include additional user options such as parallel hybrid and conventional vehicles, with appropriate user documentation
Incorporation of CHPSET codes into failure modes and effects analysis (FMEA)	Enhancement of system reliability and mitigation of effect of component failures	Risk priority numbers	Identification of potential failure modes

Design-specific, skid-mounted hardware emulators of Future Combat System	Enhancement of emulator fidelity	Resemblance of emulation hardware to notional, demonstrator-level hardware	Development of design specifics for notional, demonstrator-level systems

Appendix A

Agenda of the Committee's Data-Gathering Workshop

Combat Hybrid Power Systems Technologies
National Materials Advisory Board
National Research Council

August 26-27, 2002

Double Tree San Jose
2050 Gateway Place
San Jose, California 95110

August 26, 2002

7:30 a.m.	Registration Begins (Continental Breakfast)
8:30	Welcome and Remarks: Robert Guenther, Duke University, Chair, National Research Council Committee on Assessment of Combat Hybrid Power Systems
	System Overviews Session Chair—Robert Guenther
8:45	Integrating Combat Hybrid Power Technologies into Future Combat Systems: William Siegel, SAIC
9:15	Combat Hybrid Power System Technologies: George Frazier, SAIC
10:15	Break
	Technology Overviews Session Chair—Robert Lasseter
10:30	Advanced Electric Motor Drives: Balarama Murty, General Motors R&D Center
11:00	Power Electronics for Motor Drives: Jerry Pollack, Rockwell Automation
11:30	Switching Technologies in Higher Power: Deepak Divan, Soft Switch
12:00	Lunch
	Technology Overviews (Continued) Session Chair—William Nunnally
1:00 p.m.	SiC High-temperature Wideband Gap Materials: Mike Mazzola, Mississippi State University

1:30 Energy Storage—Batteries: John Monroe, U.S. Army/TACOM; Richard Bendert, Ovonic Battery Company

2:00 Energy Storage—Capacitors: Stephen Merryman, Auburn University

2:30 Storage System Design/Modeling: John Kajs, SAIC

Breakout Sessions Overview

3:00 Breakout Sessions Charge and Assignments: Robert Guenther

3:15 Break

Breakout Sessions
3:30 to 5:30

Advanced Electric Motor Drives and Power Electronics
Session Chair—Balarama Murty, General Motors R&D Center

Switching Technologies in Higher Power
Session Chair—Robert Lasseter, University of Wisconsin

High Temperature Wide Band Gap Materials
Session Chair—William Nunnally, University of Missouri

Energy Storage—Batteries
Session Chair—Mark Ehsani, Texas A&M University
Battery Systems for DOD Applications: Tom Matty, Saft America
Energy Storage—Capacitors
Session Chair—Steven Boggs, University of Connecticut

Storage System Design
Session Chair—Michael Raleigh, Advanced Power Technologies, Inc.
Storage System Design/Modeling: Wilford Smith, SAIC

5:30 Break

6:00 to 7:00 Reception (Committee discussion with participants)

August 27, 2002

7:00 a.m. Continental Breakfast

Closed Session for Committee (Discussion of Day 1 Results and Day 2 Plans)
Session Chair — Robert Guenther
7:30 to 8:30

Breakout Sessions (Continued)
8:30 to 11:30

Advanced Electric Motor Drives and Power Electronics
Session Chair—Balarama Murty

Switching Technologies in Higher Power
Session Chair—Robert Lasseter

High Temperature Wide Band Gap Materials
Session Chair—William Nunnally

Energy Storage—Batteries
Session Chair—Mark Ehsani

Energy Storage—Capacitors
Session Chair—Steven Boggs

Storage System Design
Session Chair—Michael Raleigh

Technology Debriefs (Summary of Breakout Sessions)
Session Chair—Robert Guenther
11:30 a.m. to 1:00 p.m.

Advanced Electric Motor Drives and Power Electronics
Balarama Murty

Switching Technologies in Higher Power
Robert Lasseter

High Temperature Wide Band Gap Materials
William Nunnally

Energy Storage—Batteries
Mark Ehsani

Energy Storage—Capacitors
Steven Boggs

Storage System Design
Michael Raleigh

1:00 Lunch

Closed Session for Committee (Lunch and Report Writing)
Session Chair—Robert Guenther
1:00 to 3:30

2:00-3:30 Systems Integration Laboratory Site Visit for Workshop Attendees

3:30-5:00 Systems Integration Laboratory Site Visit for Committee

Appendix B

List of Workshop Participants

Richard Bendert
Ovonic Battery Company, Inc.

Joseph Beno
University of Texas

Jeff Bradel
Office of Naval Research

Yvonne Chen
University of Texas

Mark Crawford
University of Texas

James Dickens
Texas Tech

Deepak Divan
Softswitch

Daniel Doughty
Sandia National Laboratories

John Egermeier
Symmorphix, Inc.

Wendy Fong
Quallion, Inc.

George Frazier
SAIC

Welman Gebhart
Radience Technologies, Inc.

Steve Hafner
Saft America, Inc.

Dan Herrera
TACOM

David Horner
ERDC

Sylvia Johnson
NASA Ames Research Center

John Kajs
SAIC

Michael Lanagan
Penn State University

Fred MacDougall
Sorrento

Tom Matty
Saft America

Mike Mazzola
Mississippi State University

Ian McNab
University of Texas

Stephen Merryman
Auburn University

Eric Miller
US Marine Corps

John Monroe
TACOM

Chenniah Nanjundiah
Maxwell

John Pappas
University of Texas

Jerry Pollack
Rockwell Automation

Jody Priddy
ERDC

Henry Rack
Clemson University

Skip Scozzie
Army Research Laboratory

William Siegel
SAIC

Wilford Smith
SAIC

Scott Story
U.S. Marine Corps

Jerome Tzeng
Army Research Laboratory

Giri Venkataramanan
University of Wisconsin

Pete Walia
Northrop Grumman Corporation

Ken Ware
G-W Research Associates

Joe Wirth
Raychem Corporation (retired)

Appendix C

Biographical Sketches of Committee Members

Robert Guenther, *Chair,* is the director of applied science at Duke University. From 1997 to 1999 he was the interim director of the Duke Free Electron Laser Laboratory. His affiliation with Duke University began in 1980 as an adjunct professor while he was working for the U.S. Army Research Office (ARO) as a physicist; later he became director of the ARO Physics Division. Prior to joining ARO, he was a physicist with the U.S. Army Missile Command and McDonnell Aircraft.

Steven A. Boggs is the director and a research professor at the Electrical Insulation Research Center at the University of Connecticut. He has also been serving as an adjunct associate professor at the University of Toronto Department of Electrical Engineering since 1991. Prior to joining the University of Connecticut in 1993, Dr. Boggs was both director of Engineering and Research at Underground Systems, Inc., and vice president of Chicago Condenser Corporation. At Underground Systems, Inc., he designed the high-temperature superconducting power cable now under Electric Power Research Institute-sponsored development by Pirelli and American Superconductor. During his 12 years, from 1974 to 1987, with the Research Division of Ontario Hydro, he conducted research in the area of solid dielectrics, thermal cable design, and SF6-insulated systems.

Mehrdad (Mark) Ehsani has been professor of electrical engineering at Texas A&M University (TAMU) since 1981 and director of its Texas Applied Power Electronics Center since 1992. He is also currently the director of the Advanced Vehicle Systems Research Program in the TAMU College of Engineering. His previous work experience was as a research engineer at Argonne National Laboratory and at the Fusion Research Center in Austin, Texas. His main areas of interest include power electronics, motor drives, electric and hybrid vehicles, energy storage systems, high-voltage direct current power transmission, and pulsed power systems.

Robert Lasseter is the director of the Power System Engineering Research Center-Wisconsin. He is also a professor at the University of Wisconsin at Madison in the Department of Electrical and Computer Engineering, working on a multimillion-dollar project focused on the integration of distributed technologies. Outside of academia, he has worked closely with a diverse range of companies in the power industry, including General Electric, Westinghouse, Los Angeles Power and Water, Ontario Hydro, Hydro-Quebec, Fornas Centrais Electricas, and Siemens. His research interests focus on the application of power electronics to utility systems and on technical issues that arise from the restructuring of the power utility system.

Balarama V. Murty is a principal research engineer with General Motors R&D Center. He has been with GM since 1979, conducting research and development in power electronics, drives systems and control. He is the chairman of the FreedomCAR Electrical & Electronics Technical Team, a colloborative effort between USCAR and Department of Energy, responsible for developing low-cost electrical drives and power inverter modules. He was also the team leader for a similar activity on the GM/DOE Hybrid Propulsion System. He is an active member of the 42 V Innovation team at GM. He has held various faculty positions in Electrical Engineering Department at the the Indian Institute of Technology, Kharagpur, India, during a distinguished academic career till 1978, the last one being a Full Professor. He was a Visiting Scientist at the University of Manitoba, Canada during 1978-79. He was honored to be a Fellow of IEEE 'for his contributions to automotive power electronics systems and electrical drives'. He has been a member of several committees of IEEE and a past vice president of Power Electronics Society during 1994-96.

William C. Nunnally is a professor of electrical engineering at the University of Missouri in Columbia. From 1974 to 1985 he led research at Los Alamos National Laboratory, and from 1985 to 1996 he taught at the University of Texas at Arlington, where he was also the director of the Applied Physical Electronics Research Center. He also consults for numerous groups, including the University of Texas Institute for Advanced Technology, Kaiser Electronics, American Advanced Technologies, and Science Applications International Corporation.

Michael Raleigh is a senior scientist with Advanced Power Technologies, Inc. (APTI) and a technical adviser in areas of pulsed power engineering and mechanical design. Prior to joining APTI in 1999, he was with Utron, Inc., as a principal investigator for hypervelocity gun research and programs applying pulsed power technology to refractory materials bonding and removal of coatings. He has also worked for General Dynamics Defense Systems; GT-Devices, a subsidiary of General Dynamics Land Systems; the Naval Research Laboratory; and the Federal Power Commission. He has a total of 27 years experience in the design and execution of experiments in the areas of interior ballistics, pulsed power, charged particle beam propagation, and plasma confinement, and diagnostic techniques associated with such experiments.

Appendix D

List of Acronyms

AFE	antiferroelectric
BOPP	biaxially oriented polypropylene
CAD	computer-aided design
CCTT	Close Combat Tactical Trainer
CHP	constant horsepower
CHPS	Combat Hybrid Power System
CHPSET	CHPS code set
CTE	coefficient of thermal expansion
CVD	chemical vapor deposition
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DoD	Department of Defense
EMC	electromagnetic compliance
EMI	electromagnetic interference
ERDC	U.S. Army Engineer R&D Center
ESR	equivalent series resistance
ETC	electrothermal chemical
FCS	Future Combat System
FE	ferroelectric
FET	field effect transistor
FMEA	failure modes and effects analysis
GTOs	gate turn offs
HE	high-energy
HEMT	high electron mobility transistor
HP	high-power
HMMWV	"Hummer" vehicle system
HVPE	hydride vapor phase epitaxy
IGBT	insulated gate bipolar transistor
JMASS	Joint Modeling and Simulation System
LED	light emitting diode
LEO	lateral epitaxial overgrowth
MBE	molecular beam epitaxy
MESFET	metal semiconductor field effect transistor
MLC	multilayer ceramic capacitors
MOCVD	metal organic chemical vapor deposition
MOSFET	metal oxide semiconductor field effect transistor
MRS	Mission Rating Speed
M&S	modeling and simulation
NCV	Notional Concept Vehicle
NRC	National Research Council

NRMM	NATO Reference Mobility Model
PE	polyethylene
PLZST	lead lanthanum zirconate stannate titanate
PM	permanent magnet
PZT	lead zirconate titanate
R&D	research and development
RSTV	Reconnaissance Surveillance Targeting Vehicle
SAFT	a battery manufacturing company
SAIC	Science Applications International Corporation
SIL	System Integration Laboratory
TE/GVW	tractive effort-to-gross vehicle weight ratio
USABC	U.S. Advanced Battery Consortium
WBG	wideband gap