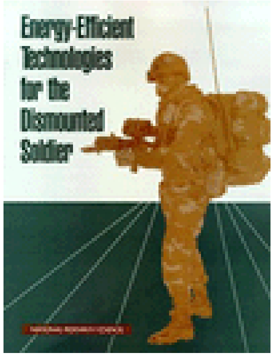
http://www.nap.edu/catalog/5905.html

We ship printed books within 1 business day; personal PDFs are available immediately.



Energy-Efficient Technologies for the Dismounted Soldier

Committee on Electric Power for the Dismounted Soldier, National Research Council

ISBN: 0-309-59127-9, 286 pages, 8.5 x 11, (1997)

This PDF is available from the National Academies Press at:
http://www.nap.edu/catalog/5905.html

Visit the National Academies Press online, the authoritative source for all books from the National Academy of Sciences, the National Academy of Engineering, the Institute of Medicine, and the National Research Council:

- Download hundreds of free books in PDF
- Read thousands of books online for free
- Explore our innovative research tools – try the "Research Dashboard" now!
- Sign up to be notified when new books are published
- Purchase printed books and selected PDF files

Thank you for downloading this PDF. If you have comments, questions or just want more information about the books published by the National Academies Press, you may contact our customer service department toll-free at 888-624-8373, visit us online, or send an email to feedback@nap.edu.

This book plus thousands more are available at http://www.nap.edu.

Copyright © National Academy of Sciences. All rights reserved.
Unless otherwise indicated, all materials in this PDF File are copyrighted by the National Academy of Sciences. Distribution, posting, or copying is strictly prohibited without written permission of the National Academies Press. Request reprint permission for this book.

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Energy-Efficient Technologies for the Dismounted Soldier

Committee on Electric Power for the Dismounted Soldier
Board on Army Science and Technology
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is interim president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

This is a report of work supported by Contract DAAM01-96-K-0002 between the U.S. Army Chemical and Biological Defense Command, and the National Academy of Sciences. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for the project.

International Standard Book Number 0-309-05934-8

Library of Congress Catalog Card Number 97-80862
Limited copies are available from:
Board on Army Science and Technology
National Research Council
2101 Constitution Avenue, N.W.
Washington, DC 20418
(202) 334-3118

Additional copies are available for sale from: National Academy Press Box 285 2101 Constitution Ave., N.W. Washington, DC 20055 800-624-6242 or 202-334-3313 (in the Washington Metropolitan Area)

Printed in the United States of America.

Cover photo: Land Warrior, courtesy of Mr. Michael Doney, U.S. Army Project Manager-Soldier, Ft. Belvoir, Virginia.

COMMITTEE ON ELECTRIC POWER FOR THE DISMOUNTED SOLDIER

JOSEPH E. ROWE, *Chair,* University of Dayton Research Institute (retired), Dayton, Ohio
JAMES D. MEINDL, *Vice Chair,* Georgia Institute of Technology, Atlanta
HAMILTON W. ARNOLD, Bell Communications Research, Inc., Red Bank, New Jersey
ROBERT W. BRODERSEN, University of California, Berkeley
ELTON J. CAIRNS, Lawrence Berkeley National Laboratory, Berkeley, California
PAUL G. CERJAN, Lockheed Martin Corporation, Arlington, Virginia
WALTER L. DAVIS, Motorola, Inc., Austin, Texas
CHARLES W. GWYN, Intel Corporation, Santa Clara, California
DEBORAH J. JACKSON, Jet Propulsion Laboratory, Pasadena, California
MILLARD F. ROSE, Auburn University, Auburn, Alabama
ALVIN J. SALKIND, Rutgers, The State University of New Jersey, Piscataway
DANIEL P. SIEWIOREK, Carnegie-Mellon University, Pittsburgh, Pennsylvania
NELSON R. SOLLENBERGER, AT&T Labs-Research, Holmdel, New Jersey
WILLIAM F. WELDON, University of Texas, Austin
NANCY K. WELKER, National Security Agency, Fort Meade, Maryland

Board on Army Science and Technology Liaison

CLARENCE G. THORNTON, Army Research Laboratories (retired)

Staff

ROBERT J. LOVE, Study Director
DUNCAN M. BROWN, Technical Writer
CECELIA L. RAY, Senior Project Assistant

BOARD ON ARMY SCIENCE AND TECHNOLOGY

CHRISTOPHER C. GREEN *Chair,* General Motors Corporation, Warren, Michigan
WILLIAM H. FORSTER, *Vice Chair,* Northrop Grumman Corporation, Baltimore, Maryland
ROBERT A. BEAUDET, University of Southern California, Los Angeles
GARY L. BORMAN, University of Wisconsin, Madison
LAWRENCE J. DELANEY, Consultant, Potomac, Maryland
MARY A. FOX, University of Texas, Austin
ROBERT J. HEASTON, Guidance and Control Information Analysis Center (retired), Naperville, Illinois
KATHRYN V. LOGAN, Georgia Institute of Technology, Atlanta
THOMAS L. McNAUGHER, The Arroyo Center, RAND Corporation, Washington, D.C.
NORMAN F. PARKER, Varian Associates (retired), Cardiff by the Sea, California
STEWART D. PERSONICK, Bell Communications Research, Inc., Morristown, New Jersey
MILLARD F. ROSE, Auburn University, Auburn, Alabama
HARVEY W. SCHADLER, General Electric Corporation, Schenectady, New York
CLARENCE G. THORNTON, Army Research Laboratories (retired), Colts Neck, New Jersey
JOHN D. VENABLES, Venables & Associates, Towson, Maryland
ALLEN C. WARD, Ward Synthesis Inc., Ann Arbor, Michigan

Staff

BRUCE A. BRAUN, Director
ROBERT J. LOVE, Study Director
MARGO L. FRANCESCO, Administrative Associate
ALVERA V. GIRCYS, Financial Associate
CECELIA L. RAY, Senior Project Assistant

About this PDF file: This new digital representation of the original work has been recomposed from XML files created from the original paper book, not from the original typesetting files. Page breaks are true to the original; line lengths, word breaks, heading styles, and other typesetting-specific formatting, however, cannot be retained, and some typographic errors may have been accidentally inserted. Please use the print version of this publication as the authoritative version for attribution.

Copyright © National Academy of Sciences. All rights reserved.

Preface

One of the critical problems facing soldiers on the battlefields of the twenty-first century will be the availability of sufficient electric power to support their needs in an information-rich environment that will require voice, data, and image transmissions over extended distances. In many instances, soldiers will have to function for extended periods of time, days or even weeks, totally detached from any supporting platform. This will require not only the continued development of battery cells, fuel cells, fueled systems, hybrids, and chargers but also the development of technologies that require less energy. There is no single or simple solution to the problem of providing adequate electric power to the dismounted soldier.

This study examines all relevant technologies that might be used on the battlefield and considers the requirements for the Land Warrior Program as a starting point for assessing the energy needs of dismounted soldiers. Two time frames are considered: 2000 to 2015 (Force XXI and Land Warrior upgrades) and 2015 to 2025 (the Army After Next).

The task statement from the Deputy Assistant Secretary of the Army for Research and Technology requested that the National Research Council, through the Board of Army Science and Technology of the Commission on Engineering and Technical Systems, carry out a study addressing multidisciplinary approaches to working within the power limitations of the dismounted soldier on future battlefields. The study included the following tasks:

- meet with the Army and the Army research community to determine the basic requirements underlying the demand and consumption of electric power by the dismounted soldier on post-digitization battlefields
- identify technologies applicable to the availability and consumption of electric power, including technologies that may have been overlooked in previous studies (that considered only energy storage and delivery)

- provide an integrated assessment of the state of the art in the applicable technology areas and an assessment of commercial research and development capabilities and the likelihood that they will meet Army requirements
- develop advanced concepts for optimizing the availability and consumption of electric power for the dismounted soldier (consider the net gains that could be realized through low power electronics, C^4I systems design and application, and advances in information technology or doctrine).
- develop strategic research objectives and a conceptual plan to guide the Army in light of what the scientific and industrial community at large is likely to accomplish.

Participants in the study were selected from many disciplines in anticipation of the broad array of technologies that needed to be addressed. From the outset, it was noted that the National Research Council was not tasked to identify or describe the evolution of new systems; rather, it was charged to identify and assess technologies likely to affect soldier energy needs in the future. The Army was called upon to describe its requirements and the role of dismounted soldiers in both near- and far-terms, and the NRC relied upon experts in technology development to describe advanced energy concepts.

A study plan was developed to respond to each element of the task statement. Meetings with the Army and other agencies were held at locations central to subject matter experts. The National Research Council in Washington, D.C. was the site of five meetings. The U.S. Army Communications-Electronics Command Research, Development and Engineering Center at Fort Monmouth, New Jersey, hosted two fact-finding sessions. The Motorola Government Systems Group in Scottsdale, Arizona, hosted a third fact-finding session. Specific presentations are listed in Appendix A.

The study committee formed four panels to assess different technology areas and to develop advanced concepts for power. The Energy Sources and Systems Panel focused on the supply side; the other three panels (Networks, Protocols and Operations; Communications, Computers, Displays and Sensors; and Low Power Electronics and Design) focused on technologies with the potential to reduce demand. After each panel made its assessment, the findings were integrated into a cohesive assessment of possibilities for the time frames represented by Force XXI and the more distant Army After Next. Frequent communication among participants to resolve differences of opinion were facilitated by electronic mail and teleconferencing. Army staff members at all locations were very helpful in providing critical information.

Joseph E. Rowe, *Chair*
Committee on Electric Power for the Dismounted Soldier

Contents

APPENDICES

Figures and Tables

Figures

Tables

Acronyms and Abbreviations

ACRONYMS

A/D	analog to digital
AAN	Army After Next
ACTD	advanced concept technology demonstrations
AMC	Army Materiel Command
AMCLD	active matrix liquid crystal display
AMEL	active matrix electroluminescent display
AMPS	advanced mobile phone system
AMTEC	alkali-metal-thermal-to electrical converter
APS	active pixel sensor
APU	auxiliary power unit
ARL	Army Research Laboratory
ARO	Army Research Office
ASIC	application-specific integrated circuits
AWE	advanced warfighting experiment
BSF	back surface fields
BSR	back surface reflectors
C^4I	Command, Control, Communications, Computers, and Intelligence
CAD	computer-aided design
CCD	charge coupled device
CDL	chemical double layer
CDMA	code division multiple access
CFM	contamination-free manufacturing
ChLCD	cholestric liquid crystal display
CIS	copper indium diselenide
CISC	complete instruction set computer
CMOS	complementary metal-oxide semiconductor
COTS	commercial off-the-shelf
CPU	central processing unit
CRT	cathode ray tube

DARPA	Defense Advanced Research Products Agency
DBS	direct broadcast satellite
DC	direct current
DIICOE	Defense Information Infrastructure Common Operating Environment
DMFC	direct methanol fuel cell
DoD	U.S. Department of Defense
DoE	U.S. Department of Energy
DRAM	dynamic random access memory
DSP	digital signal processor
DVO	direct view optic
ESR	equivalent series resistance
EPR	equivalent parallel resistance
FDD	frequency division duplex
FET	field effect transistor
FM	frequency modulation
GPHS-RTG	general-purpose heat source-radioisotope thermal generator
GPS	global positioning system
GSI	gigascale integration
GSM	Global System for Mobile Communications
GSO	geosynchronous orbit
HDTV	high-definition television
HF	high frequency
I/O	input/output
IC	integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
IF	intermediate frequency
IHAS	integrated helmet assembly subsystem
IR	infrared
IS-54, -95	Interim Standard (Telecommunications Industry Association)
ISM	integrated sight module
LAN	local area network
LCD	liquid crystal display
LED	light emitting diode
LEO	low earth orbit
LPD	low probability of detection
LPI	low probability of intercept
MEMS	microelectromechanical systems
MOD-RTG	modified radioisotope thermal generator

MOSFET	metal-oxide semiconductor field effect transistor
MOUT	military operations in urban terrain
MPEG2	Motion Picture Experts Group
Nd:YLF	neodymium: yttrium lithium fluoride
NMOS	N-type metal-oxide semiconductor
NRC	National Research Council
NTRS	National Technology Roadmap for Semiconductors
OMS	operational mode summary
PACS	personal access communications systems
PAFC	phosphoric acid fuel cell
PACS-UB	PACS unlicensed B version
PC	personal computer
PCMCIA	Personal Computer Memory Card International Association
PCS	personal communications systems
PDA	personal digital assistant
PEMFC	proton exchange membrane fuel cell
PMOS	P-type metal-oxide semiconductor
QPSK	quadrature phase shift keying
R&D	research and development
RAM	random access memory
RDEC	Research, Development and Engineering Center
RF	radio frequency
RIPD	remote input pointing/positioning device
SIA	Semiconductor Industry Association
SINCGARS	Single Channel Ground and Airborne Radio System
SNR	signal-to-noise ratio
SOI	silicon on insulator
SRAM	static random access memory
SSCOM	Soldier Systems Command
TCAD	technology computer-aided-design
TCIM	tactical communications interface module
TDD	time division duplex
TDMA	time division multiple access
TEC	thermoelectric cooler
TPV	thermophotovoltaics
TRADOC	Training and Doctrine Command
TSI	terascale integration

UAV	unmanned aerial vehicle
ULPE	ultra-low power electronics
VHF	very high frequency
VRD	virtual retinal display

ABBREVIATIONS

μ	micro
μm	micrometer
μW	microwatt
A	ampere
Ah	ampere hour
C	centigrade
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
dB	decibel
F	farad
g	gram
GHz	gigahertz
Hz	Hertz
in^3	cubic inches
J	joule
K	Kelvin
kb	kilobit
kbps	kilobits per second
kHz	kilohertz
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
l	liter

m^3	cubic meter
Mb	megabit
Mbps	megabits per second
Mbytes	megabytes
mg	milligram
MHz	megahertz
MIPS	million instructions per second
mJ	millijoule
mm	millimeter
mm^2	square millimeter
ms	millisecond
MV	megavolt
MW	megawatt
mW	milliwatt
nm	nanometer
pF	picofarad
ppm	parts per million
psi	pounds per square inch
V	volt
W	Watt
Wh	Watt hour

Executive Summary

The Committee on Electric Power for the Dismounted Soldier, under the auspices of the Board on Army Science and Technology of the National Research Council, examined the power requirements of the dismounted soldier in both the near- to mid-term (to 2015) and the longer term (to 2025). In the process, the committee reviewed both energy supplying technologies such as batteries and fueled systems, and energy-consuming technologies such as communications, sensors, and computers. In each of these areas, the committee assessed the potential for commercial technology to meet the Army's needs and tried to determine what it would take for the Army to take full advantage of commercial technology.

LAND WARRIOR AND DISMOUNTED SOLDIER REQUIREMENTS

The Army Land Warrior system, which includes a computer/radio subsystem, an integrated helmet assembly subsystem, and a weapons subsystem, is being developed to increase the effectiveness of the dismounted soldier on the battlefield. The system is integrated by a general-purpose computer similar to a laptop personal computer and consists of radios, display systems, sensors, and other electronics (shown in Figure ES-1). In the field, the Land Warrior system is expected to weigh approximately 40 pounds and draw more than 50 W of electricity with all subsystems operating. Land Warrior will be used by all members of an infantry squad, the basic Army combat unit.

The first Land Warrior units are scheduled to be fielded in 1999. The Army expects to have 34,000 in service by the year 2003. Because the complete ensemble will include all of the electronics that will require power for the dismounted soldier, the committee used the Land Warrior system as a baseline for analyzing near- and mid-term power requirements on the battlefield.

The Army Soldier System Command (SSCOM) is responsible for meeting requirements for the "soldier as a system." The SSCOM Project Manager-Soldier, at Fort Belvoir, Virginia, is responsible for coordinating the engineering and manufacturing development of the Land Warrior system with a program for the

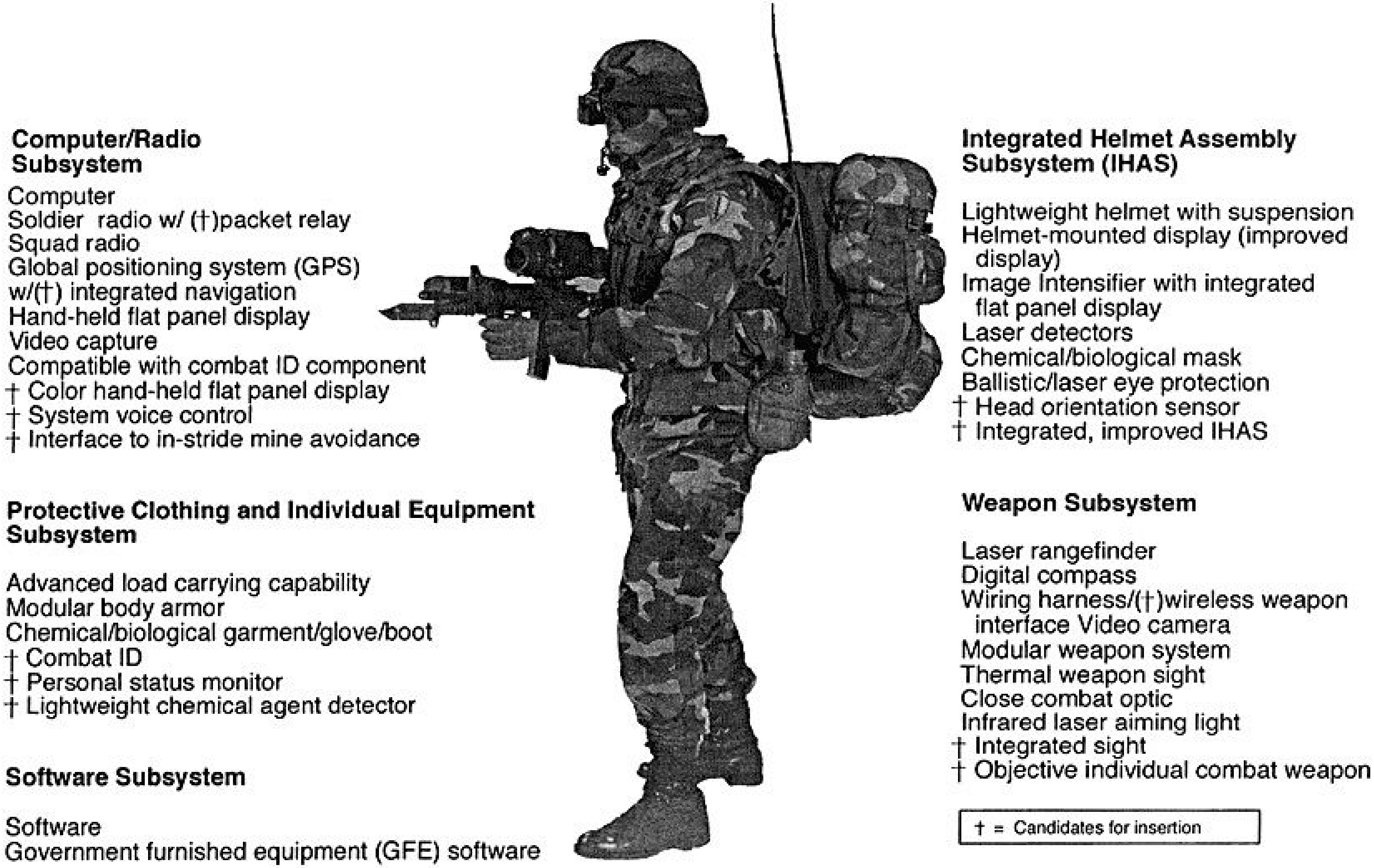


FIGURE ES-1 Land Warrior subsystems. Source: Doney, 1996.

insertion of new technology, under the direction of the Natick Research, Development and Engineering Center in Natick, Massachusetts. Advanced concept technology demonstrations and advanced warfighting experiments involving new power sources and electronics, many of them developed by the Army Communications-Electronics Command, are being conducted in tandem with the Land Warrior program to help finalize the system design.

Ongoing "digitization" experiments to incorporate information technologies are helping to bring the power requirements for dismounted soldier systems into focus. Electronics being developed to enhance command and control, survivability, lethality, mobility, and sustainment will increase the demand for energy on the battlefield into the Army After Next time frame (to 2025). The dismounted soldier, in both the near- and far-term, will require a combination of energy sources and electronic systems that will extend the range and duration of operations, enable substantial reductions in weight and bulk, and minimize the soldier's vulnerability to detection by the enemy.

APPLICABLE TECHNOLOGY AREAS

The committee was organized into panels representing the four general technology areas necessary for meeting the energy needs of the dismounted soldier: energy sources and systems; low power electronics and design; communications, computers, sensors, and displays; and networks, protocols, and operations. After assessing the technologies in each area, the committee found that efforts to improve the efficient use of energy are likely to be substantially more successful than efforts to increase the supply of energy.

Energy Sources and Systems

Of the compact energy supply systems the committee considered, rechargeable batteries and fuel cells, the principle energy sources today, are likely to continue to be used for the foreseeable future. The initial Land Warrior systems will be powered by nonrechargeable, Army-standard batteries with specific energy of 150 Wh/kg. In the near future, lithium rechargeable batteries will approach 200 Wh/kg and will have longer lifetimes than today's rechargeable batteries. For missions beyond the capacity of batteries, small fuel cell systems that exploit the higher specific energies of liquid and gaseous fuels will be used as battery chargers. These systems weigh as little as 2.5 kg (including fuel and intermediate storage battery).

Other technologies with high potential for future soldier energy systems include thermophotovoltaic (TPV) systems, alkaline-metal thermal-to-electric converters (AMTEC), microturbines, and human-power systems. The Army's immediate goal should be to develop a hybrid system consisting of a fueled primary source and a rechargeable battery for intermediate storage.

Low Power Electronics and Design

The Semiconductor Industries Association National Technology Roadmap for Semiconductors, a guideline updated every three years, has charted dramatic increases in the number of transistors per chip by as much as 8 orders of magnitude (10^8, or a factor of 100,000,000) compared with 1960. Since 1960, the semiconductor industry —with the help of federal funding for research and development—has cut the feature size of integrated circuits in half every six years and is expected to continue at that pace until at least 2005. The primary industry goal has been to enable vastly more complex "systems on a chip," and this has led the industry to search for ways to reduce energy dissipation by adopting lower voltage standards for operation and reducing or eliminating interconnections.

The resulting energy-efficient technologies have increased the capabilities and reduced the weight of electronics systems. New computer-aided design tools that minimize power complement the advances in low power electronics. For example, a basic application-specific integrated circuit design can be implemented in a high level design language, and the design can simply be recompiled periodically in the latest circuit technology. Also, low power software can be specifically coded to minimize energy consumption.

Communications, Computers, Displays, and Sensors

Commercial developers have learned that they can meet stringent military requirements, such as reduced bulk, weight, and cost, by actively pursuing more energy-efficient systems. Consumer products, such as cellular phones, pagers, and personal digital assistants, have a strong focus on energy efficiency and provide functional capabilities comparable, and in many cases superior to, those likely to be developed or adapted by the Army.

With all subsystems operating simultaneously, the Land Warrior radios, computer, displays, and sensors are estimated to have a total power requirement of more than 50 W. The committee determined that a notional system of comparable functions based on available commercial technologies could be built before 2001 with a total system power requirement of less than 4 W. This order-of-magnitude difference would not involve breakthroughs in technology but would require the Army to focus on energy efficiency as a primary design goal.

The Land Warrior system architecture is handicapped by relying on a single general-purpose computer to perform computational, signal processing, and radio interface tasks. The soldier computer would be in continuous operation with estimated power requirements of 15 W. Following the commercial trend of using low power, dedicated, special-purpose processors in the radios, sensors, and other subsystems and using state of the art fabrication technology would cut the computer operating power requirement to 100 mW. Power requirements for computing are expected to decline rapidly in the coming decades, and the committee estimates that a computer with substantially greater functionality, including a voice-recognition interface, would require only 1 mW by the year 2015.

Transmitters in the soldier and squad radios present the greatest challenge to energy saving because the energy needed to transmit a bit is set by physical limits. The power requirements increase rapidly with distance, yet future operations doctrine will increase the distances involved in squad operations and increase bandwidth and data rate requirements. Thus although the energy costs of computing, sensing, and displaying are likely to decline rapidly, the energy for wireless transmissions will increase and eventually dominate the energy demand of the dismounted soldier systems.

Networks, Protocols, and Operations

Systems considerations, including the design and operation of network architectures and data communication protocols, can substantially reduce the power requirements for battlefield communications. Savings can also be achieved by reducing the time that subsystems are in standby mode "listening" for relatively infrequent stimuli. Computers and radios could be placed in "sleep mode" with technology similar to that of cellular telephones and pagers.

Using a peer-to-peer architecture, the radio network could be optimized to distribute communications and computing tasks among network terminals. Energy use could be concentrated in a designated master terminal to minimize the power required by the network as a whole. The master terminal would synchronize all of the soldier terminals, so that each terminal would only have to wake up for 1 millisecond of every 20 to 100 milliseconds to check for traffic and could sleep in the intervals.

A "multihop" architecture (using intermediate signal repeaters to transmit information between widely separated terminals) would lower energy consumption by reducing transmission ranges. The algorithms are complex, but they are already being investigated under Defense Advanced Research Products Agency (DARPA) sponsorship. As the energy cost of computing declines, trade-offs between computing and communications capabilities could be made to improve the energy efficiency of dismounted soldier systems.

Terrestrial wireless communications could be supplemented by other means, such as emerging multisatellite systems, which would give soldiers access to a global network in addition to the high-bandwidth soldier network. Direct broadcast satellite technology might also be adapted.

ADVANCED CONCEPTS

The Land Warrior system will fall short of the vision of the digitized battlefield because of excessive power requirements for computation and radio transmission. The program is on a course to field subsystems that, by and large, are heavier, bulkier, and less functional than comparable systems that could be built using commercial consumer technologies. Over time, as commercial products continue to improve and possess capabilities that the Army is unable to field for itself, a crisis of major proportions will emerge. Energy availability may actually increase, but the Army will be unable to use the available energy-efficiently to achieve either its current objectives or future objectives for dismounted soldier operations.

This crisis has two components. The first involves the realization of current goals, such as battlefield digitization, and the relationship of these goals to the electrical energy used by the dismounted soldier. Unless a dramatic shift is made in the design of the soldier system and in the associated doctrine, the amount of energy storage required will preclude soldier mobility, even with expected advances in energy source technologies.

Second, unless the Army is able to exploit and track commercial technology in Army-specific designs, potential adversaries will be able to acquire capabilities superior to those available to the Army from commercial sources. Even more troublesome is that the Army will have to do more than catch up with and match commercial technologies. The Army's equipment must have a competitive edge over the equipment of potential adversaries.

Advanced energy concepts can only be realized if the Army focuses on energy use, just as successful commercial developers have. The Army will have to make three essential paradigm shifts:

- Energy strategy. The Army must focus on energy-consuming systems as well as energy source systems.
- System design. The Army must use a design approach that optimizes for energy use at all levels of the system design.
- Use of commercial technology. The Army must capitalize on advances in energy-efficient consumer electronics by using open system designs to simplify the incorporation and use of commercial data-processing and communications technology.

RESEARCH OBJECTIVES

Research objectives aimed at meeting Army power requirements are listed in Table ES-1. The committee determined that three of these are essential to the combat effectiveness of the future dismounted soldier and offer the highest potential to influence Army After Next capabilities:

- development of a wireless communications network architecture for the battlefield that directly exploits commercial technology
- development of modeling and simulation capabilities to gauge the energy use of dismounted soldier systems
- continuation of active research to develop advanced fueled systems

TABLE ES-1 Research Objectives

	Near Term	Far Term	Commercial Research Lever	Military-Specific Application
Energy Sources and Systems				
Rechargeable batteries	X		X	X
Fuel cells	X			X
Advanced fueled systems[a]		X		X
Human-powered systems		X		X
Low Power Electronics and Design				
Design tools for minimizing power consumption	X		X	X
Architectural level design tools	X		X	X
Packaging to minimize interconnects		X	X	X
Submicron lithography		X	X	
Optimizing device design		X	X	
Design methodologies for Army "systems on a chip"		X	X	
Communications, Computers, Displays, and Sensors				
Terminal equipment architectures	X		X	X
Component and human computer interfaces		X	X	X
Ultra-low power displays and sensors		X		X
Multimodal and adaptive communication circuits	X		X	
Evolution of hardware and software		X	X	
Networks, Protocols, and Operations				
Wireless battlefield communications network[a]		X		X
Extending range of the dismounted soldier		X	X	X
Sensors and software for power management	X		X	X
Models for optimizing energy-efficiency[a]	X	X	X	X
Propagation characteristics and antenna design		X		X

[a] Objectives with highest potential.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion 1. The power requirements of the Land Warrior system will limit the effectiveness of dismounted soldiers on the digitized battlefield.

This study has shown that the Land Warrior system is far less energy efficient than it could be. It will fall short of meeting the needs of the digitized battlefield principally because of excessive energy demands for computation and radio transmission. The Land Warrior program is on a course to field subsystems that are heavier, bulkier, and less functional than they would be using state of the art consumer technology. This is because the Army has failed to address energy efficiency in system and subsystem designs. The Land Warrior program provides for the incorporation of advanced technology, but the scope of necessary enhancements will require special funding and command emphasis by the Army.

Commercial equipment is available with the energy efficiencies the dismounted soldier needs. The Army cannot continue to rely primarily on improvements in energy storage, which only mask equipment inefficiencies. A coherent approach to prevent the problem from growing to crisis proportions will require concerted efforts by both the Army Acquisition Executive and the Army Materiel Command.

Recommendation 1a. Army leadership must emphasize the importance of reducing energy demand to achieve energy sufficiency for future dismounted soldiers. Meeting near- and far-term needs will require major changes in Army thinking. Paradigm shifts in energy strategy, system design, and the use of commercial technology are absolutely essential to avert a crisis. The new paradigms must be translated into top-down initiatives.

Recommendation 1b. The Army should accelerate the development and insertion of enhancements to the Land Warrior system, focusing on improvements to the computer/radio subsystem because the estimated power requirements for communications and computing functions in Land Warrior are clearly excessive.

Recommendation 1c. The Army Acquisition Executive should make energy efficiency a priority consideration in evaluating contractor performance in future procurements of electronics for the dismounted soldier.

Conclusion 2. Advanced fueled systems and energy-efficient technologies are both necessary to achieve energy sufficiency for soldiers in the Army After Next time frame.

Dramatic improvements in the energy efficiency of systems for the dismounted soldier are already available as a result of advances in low power electronics and commercial consumer technologies. Reducing energy consumption will mean that available energy sources will be able to support longer missions using smaller and lighter energy sources and that new functions can be added to increase the soldier's capabilities. Paying attention to energy consumption through equipment design, as well as increased awareness and enforcement of power discipline, will also yield ancillary benefits, including lighter components, reduced susceptibility to detection, lower cooling requirements, and simplified logistical support. These dramatic improvements, combined with limited increases in the specific energy of sources and improved storage capabilities afforded by advanced fueled sources, will make energy sufficiency possible for dismounted soldiers in the Army After Next even for the most problematic requirement, microclimate cooling.

Recommendation 2a. To achieve energy sufficiency, the Army should set research objectives that focus on energy-efficient technologies. Energy efficiency is the key to success for the Army After Next.

Recommendation 2b. The Army should support use of computer-aided design tools for systems and integrated circuits specifically optimized for low power performance. If the necessary design tools are not available commercially, the Army should support its own development programs, perhaps in conjunction with related DARPA efforts. Army contractors for electronic systems should be required to use energy-optimizing design tools.

Recommendation 2c. The Army should support the development of mission-specific software for dismounted soldier systems. General-purpose software is wasteful and not energy-efficient.

Recommendation 2d. The Army should support the development and use of low power software, in which each instruction is written or compiled to minimize power requirements. New tools may be required for specific military applications.

Recommendation 2e. The Army should use dedicated electronic circuits wherever possible to minimize power requirements. Application-specific integrated circuit (ASIC) technology can achieve the efficiencies of custom circuits and hardware and still be cost effective.

Recommendation 2f. The Army should establish and enforce standards of awareness and discipline for energy consumption in dismounted soldier operations.

Conclusion 3. Access to commercial technology must be improved.

The Army will not be able to meet the goal of digitizing the battlefield unless it improves its ability to adapt and benefit from commercial consumer technology. Subsystems in the Land Warrior system, for example, will be obsolete compared with commercially available consumer electronics before the system is fielded. Military radios that meet the strict definition of commercial off-the-shelf equipment in most cases are not built to the same energy efficiency standards as consumer electronics. The fact that Army developers or suppliers of military electronics also develop, produce, and market consumer electronics is no guarantee that advances in consumer electronics will be carried over into military systems. The committee found that the consumer and military business units of large corporations are substantially and deliberately isolated from each other and that technology used in military systems sometimes lags substantially behind the technology in consumer systems produced by the same company.

The Army, through the science and technology insertion component of the Land Warrior program, recognizes the need to build flexibility into the process for acquiring advanced technology. Institutional provisions for experimentation, such as the Advanced Warfighting Experiment at Fort Hood, and spiral developments providing for continuous design feedback, can accelerate the incorporation of applicable technologies.

Recommendation 3a. Army procurement strategy should include provisions for keeping pace with advances in the semiconductor industry. Even if it is fielded in increments, state of the art technology should be fielded in small quantities so that systems can be upgraded frequently. In addition to requiring energy-efficient technologies, Army design and procurement contracts should require contractors to adopt improved technology automatically as it becomes available.

Recommendation 3b. The Army should support efforts to maintain the pace set by the National Technology Roadmap for Semiconductors. The road map is a key means of ensuring continued superiority in electronics technology by defining critical technology areas and research gaps that may stand in the way of needed breakthroughs. The Army should:

- Use the road map to project technology availability in specifying new systems.
- Support research and development in industry and universities in areas identified as critical in the road map.
- Contribute to the road map, either directly through U.S. Department of Defense representation on the road map committee, or indirectly, through other members, such as representatives of the national laboratories.

Recommendation 3c. The Army should develop an effective strategy for keeping abreast of state of the art consumer product development and for specifying low power performance criteria in its solicitations. The Army should emphasize participation in consumer-oriented electronics industry activities that focus on low power electronics, such as conferences, symposia, and focus centers, as a way of raising awareness and expectations of energy-efficient performance. Only through participation can the Army keep abreast of technology development and, more important, influence industry priorities.

Recommendation 3d. The Army must experiment continuously to keep pace with the development of commercial equipment. Simulations should be used to determine the value of trade-offs between improvements in energy consumption and less essential equipment characteristics.

Conclusion 4. Wireless transmission will dominate energy demand in future dismounted soldier systems.

If the Army can take advantage of trends in commercial consumer electronics, the power requirements of computers, sensors, and displays for the dismounted soldier will fall to nearly negligible levels. Subsystems that perform these functions could consume less than 1 W of electricity by the year 2015. Energy needed for radio transmission will then dominate the power requirements for successor Land Warrior systems.

Recommendation 4a. The Army should refine its requirements for high-resolution images and video communications to the minimum necessary to meet battlefield needs.

Recommendations 4b. The Army should minimize wireless data transmission by reducing the time required to convey a given amount of information. Relevant technologies include speech and image compression, database caching, and information science technologies that reduce, eliminate, or automate the energy inefficient natural language (read message) transmissions that are currently used.

Recommendation 4c. The Army should adapt the hierarchical network architecture of cellular telephones to create a "virtual peer-to-peer" network, which would improve the distribution of computational resources while taking advantage of commercial cellular technologies.

Recommendation 4d. The Army should modify and synchronize operational doctrine with emerging systems to minimize soldier transmissions. For example, data collection and reduction should be performed as close to the data collector as possible, and computational components should be distributed across the network of soldier communicators. The Army should exploit energy saving communications protocols, such as the protocols used to alert radio receivers to incoming data in pagers and cellular phones. Other commercial techniques should be incorporated doctrinally to reduce or eliminate the operational demands on transmit energy.

Recommendation 4e. The Army should study alternatives for the military network design to optimize power consumption. For example, it should investigate the use of commercial low-orbit satellite systems and unmanned aerial vehicles as relatively energy-efficient alternatives that may also provide high-bandwidth capabilities.

Conclusion 5. Research to improve energy source must continue.

Improved energy sources, with higher specific energies and better performance characteristics, will be important to the dismounted soldier because the proliferation of new electronics-based systems will continue. Unlike commercial investments in microelectronics and communications technologies, commercial investments in power sources and systems technologies will probably not be sufficient because the military market is small. Therefore, military research and development will still be needed.

In the near term, the dismounted soldier must rely on both nonrechargeable and chargeable batteries for power. But batteries will not suffice for missions that require more than a kilowatt-hour (about 20 hours using the initial Land Warrior system). For high energy (long mission time) requirements, fueled systems (generally, combinations of rechargeable batteries or capacitors charged by fuel cells or other fueled energy sources) can offer specific energy an order of magnitude higher than the best battery at relatively small development risk. Hybrid systems will make it possible to optimize performance for both high power and high energy requirements.

Recommendation 5a. For the near term, the Army should continue to support research and development on rechargeable batteries with specific energy higher than 200 watt hours per kilogram.

Recommendation 5b. The Army should continue research into fueled energy sources and high-performance capacitors for use in hybrid energy supply systems for the dismounted soldier. It should develop prototypes of the most promising ones for field trials within the next decade.

Recommendation 5c. The Army should continue research for the far future across a broad range of technologies, including advanced fuel cells, microturbines, and thermophotovoltaic converters.

REFERENCE

Doney, M. 1996. Land Warrior System. Briefing by Michael Doney, U.S. Army, Project Manager-Soldier, to the Committee on Electric Power for the Dismounted Soldier, Washington, D.C. August 15, 1996.

1

Introduction

The Army has embarked on a firm course to "digitize" the battlefield by exploiting advances in communications and computer technologies to acquire, exchange, and employ timely digital information throughout the battle space. The Army expects digitization to give commanders and individual soldiers a common picture of the battle space in near real time, enabling them to speed up operations to such a degree that the enemy will be unable to react.

Dismounted soldiers, as opposed to soldiers who fight from mobile platforms, will be particularly affected by this initiative. In addition to a weapon and load-bearing equipment, dismounted soldiers of the future will carry such things as a high-capacity tactical computer; a helmet-mounted display; one or more secure, antijam radios; a global positioning system terminal; a hand-held display for color overlay map graphics; a video capture and transfer device; monitoring and detection systems; a laser rangefinder and target designators. These electronic devices will increase the demand for electric power from already limited power sources. Field commanders have always considered reliable power to be a high priority, but the energy demands associated with the new electronics on the battlefield are likely to exceed the capacity of human-portable energy sources.

Because practical capacity is limited by the laws of chemistry and physics, the Army must investigate ways to do more than increase the supply of energy. The most promising approach is to reduce energy consumption through advances in electronics technologies. Promising examples include: developing more efficient devices and circuits; using power management architectures; using low power microcircuits, sleep mode designs, and data compression techniques; using adaptive networking; and adopting energy-conservative operational concepts and procedures. Because commercial industry is already working on energy-efficient mobile communications and data processing, the Army can make substantial progress just by following industry's lead.

Energy storage technologies were reviewed by the National Research Council (NRC, 1988) in the Energy Engineering Board report, "Power Technology for the Army of the Future" (see also Zucchetto et al., 1989). The results of that study were carried forward into the Board on Army Science and Technology study, "Strategic Technologies for the Army of the Twenty-First

Century" (NRC, 1993a). Since 1990, workshops sponsored by the Army Research Office have been reviewing the state of the art to determine what is applicable to the power needs of soldiers (Space Power Institute, 1990, 1992a, 1992b, 1992c, 1994, 1996).

Prior studies and workshops have concentrated on methods for storing more energy in smaller, lighter batteries or fuel cells through the use of more energetic reactants and newer electrode, electrolyte, and packaging materials. The Army has introduced new battery technologies slowly, however, because of the limitations of fundamental chemical properties and because of safety concerns associated with operating at the high specific energies necessary for soldier applications. At the same time, advances in fuel cells may offer a tenfold improvement where substantial amounts of energy are needed over time and where fuel can be resupplied.

Batteries represent a major concern for the Army. The logistical costs of providing military batteries for the Army combat net radios during the Gulf War approached the cost of replacing the radios. Commercial batteries could reduce costs, but almost all commercial battery cells come from foreign sources and require stockpiling in bulk. The cost of batteries has become such a major issue that the Army Materiel Command (AMC) recently directed that rechargeable batteries be used wherever practical and established a goal of reducing expenditures on batteries by one-half (AMC, 1996).

APPLICABLE TECHNOLOGY AREAS

The committee reviewed and assessed technologies associated with the generation, storage, and distribution of energy, as well as technologies associated with energy usage, such as electronics design and fabrication, power management, and data communications. In particular, the committee assessed commercial technologies that might apply to the Army's plans for future dismounted soldiers. The committee divided its technology assessment into four technology areas:

- energy sources and systems
- low power electronics and design
- communications, computers, displays, and sensors
- networks, protocols, and operations

STUDY APPROACH

In assessing the power requirements of the dismounted soldier, the committee used the Land Warrior system as a baseline. The objective Land Warrior is depicted in Figure 1-1 and described in detail in Chapter 2. The Army's engineering and manufacturing development program is scheduled to begin fielding systems in 1999 with plans to deploy 34,000 by the year 2003. Land Warrior and successor dismounted soldier systems are likely to remain in the Army inventory at least through the year 2015.

FIGURE 1-1 U.S. Army Land Warrior. Source: Doney, 1996.

In addition to the mid-term possibilities represented by Land Warrior and its elaborations, the committee also considered a longer view extending to the year 2025 to project advanced energy concepts that would support revolutionary capabilities for the dismounted soldier in what the Army calls the "Army After Next." The committee formulated research objectives for meeting the anticipated power requirements and, finally, reached a consensus on conclusions and recommendations.

REPORT ORGANIZATION

The report is organized to document the committee's interpretation of Army requirements based on fact-finding activities and to provide background information and support for the conclusions and recommendations. Chapter 1 (Introduction) explains the study approach and report organization, lists applicable technologies areas, and states basic assumptions. Chapter 2 (Requirements and

Needs) discusses requirements for electric power for the dismounted soldier using the capabilities in the Army Land Warrior program as a baseline.

Chapters 3 through 6 assess technologies in the four technology areas. Chapter 3 (Energy Sources and Systems) provides a detailed assessment of compact power sources and systems advances likely to effect the availability of energy for the dismounted soldier. Chapter 4 (Low Power Electronics and Design) discusses the effect of advances in integrated circuitry manufacturing and design techniques on energy demand. Chapter 5 (Communications, Computers, Displays, and Sensors) assesses energy loss and power drain characteristics of basic hardware, and Chapter 6 (Networks, Protocols and Operations) discusses the effects of communications networks and architectures on energy demand.

Chapter 7 (Advanced Concepts) offers an integrated assessment of all technology areas, with projections of the power requirements using energy-efficient technologies in the near future (the year 2001) and in the mid-term (2015). Chapter 8 (Research Objectives) proposes specific research objectives that would enable the Army to achieve the capabilities envisioned for dismounted soldiers of the future and provide guidelines for achieving these objectives. Chapter 9 (Conclusions and Recommendations) reviews the committee's most significant findings.

ASSUMPTIONS

The committee made several assumptions at the outset of the study to focus its efforts. First, the committee defined a "dismounted soldier" as one capable of carrying the battle to the enemy independently, untethered to a supporting platform. The committee assumed that a typical dismounted soldier would be a member of an Army infantry squad and would operate with other dismounted soldiers and leaders in a pyramidal organizational structure like the one shown in Figure 1-2.

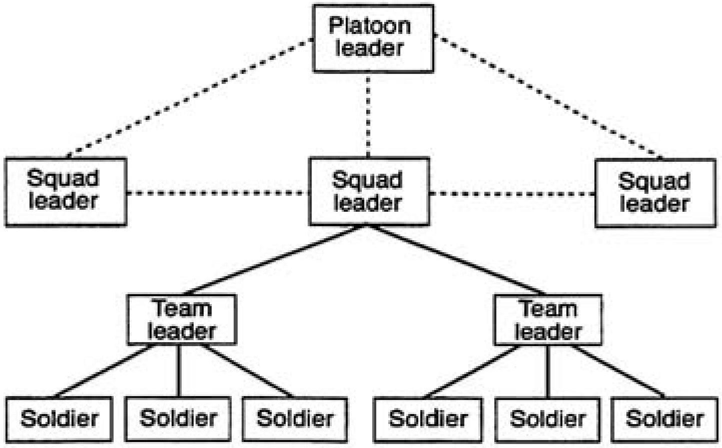


FIGURE 1-2 Organizational structure of an infantry squad.

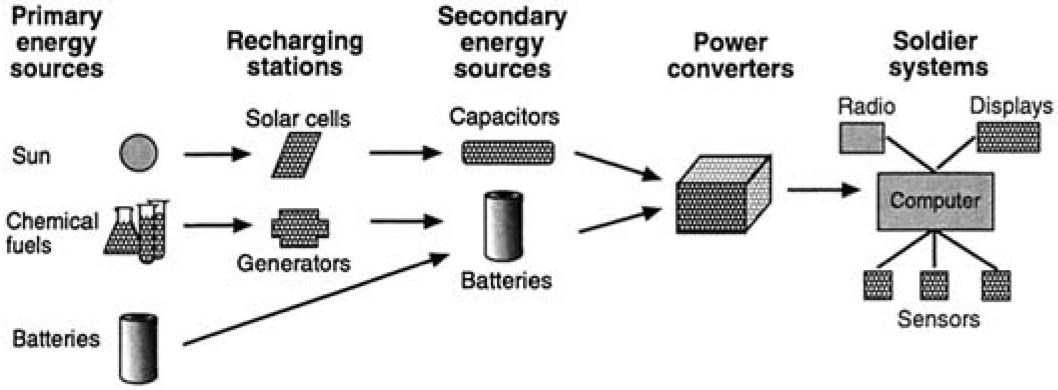


FIGURE 1-3 Energy train.

The committee also assumed that electric power for the dismounted soldier would consist of elements of an energy train from primary source to consumption, as illustrated in Figure 1-3. Each element in the train is included within the scope of the study and offers opportunities for improving the overall provision of electric power to the dismounted soldier.

SUPERIORITY THROUGH TECHNOLOGY

The Army has achieved its current superiority through the application of technology. One way to ensure full-spectrum dominance and continued superiority over the extended range of operations the Army faces in the future is to develop and field better technology than potential adversaries. Doing so will require keeping pace with rapid advances in commercial technology, especially as they become more freely available worldwide. This will challenge the way the Army develops and procures systems as never before, but the alternative is to risk becoming a second-class force.

2

Requirements and Needs

This chapter reviews the Army's requirements and needs (or unstated requirements) that are an outgrowth of the proliferation of electronic systems on the battlefield. The chapter discusses the Land Warrior program and new electronic systems that will affect power considerations for the dismounted soldier; the soldier as a system; the impact of digitization; relevant operational factors; and future initiatives and trends.

The individual soldier is the Army's ultimate weapon. In addition to being a live weapons platform, the soldier is also a source of battlefield intelligence and a vital link in command and control communications. Advances in technology have increased not only the capabilities of traditional weapons systems, but also the potential of individual soldiers to function as shooters, sensors, and communicators.

The Army's concept of the soldier as a system provides a good framework for analyzing this increased potential in terms of the individual soldier. The soldier system is comprised of systems in which all requirements can be placed in five functional categories: lethality, mobility, command and control, survivability, and sustainment (Figure 2-1).

The Soldier Systems Command (SSCOM) was established by the AMC (Army Materiel Command) exclusively to coordinate the fulfillment of soldier system requirements. SSCOM responds to the needs of soldiers in various specialties (such as artillery, tank-mounted, airborne, rear-echelon, air cavalry, and dismounted infantry), but perhaps the command's most visible undertaking is the Land Warrior program, which focuses on collective requirements of the dismounted combat soldier.

Advances in communications, computers, and other electronics technologies have spurred the Army to develop systems that will dramatically increase the effectiveness of the dismounted soldier. All of these systems will consume energy, which must be provided by human-portable sources. Therefore, the Army needs both improved energy sources and more efficient energy use.

The Army Force XXI Land Warrior program, which is administered by the SSCOM Project Manager-Soldier, at Fort Belvoir, Virginia has the highest potential impact on energy for future dismounted soldiers. This program combines the engineering and manufacturing development of the Land Warrior ensemble for the dismounted soldier with a science and technology development program (earlier known as the Generation II Soldier program), which is managed by the Army's Research, Development and Engineering Center (RDEC) in Natick, Massachusetts. Advanced concept technology demonstrations (ACTD) and advanced warfighting experiments (AWE) involving new power sources and electronics, many developed by the Army Communications-Electronics Command, at Fort Monmouth, New Jersey, are being conducted in concert with the Land Warrior program.

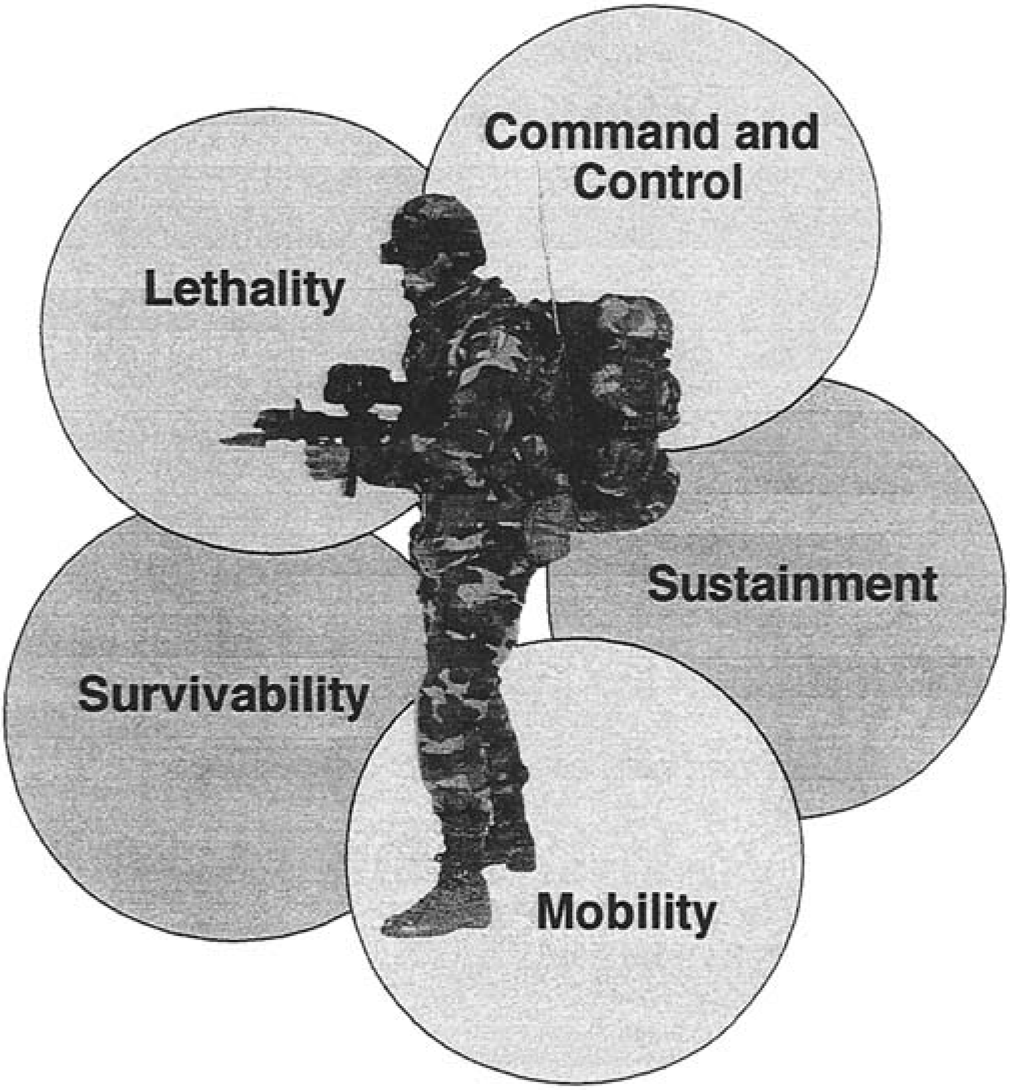


FIGURE 2-1 Requirement categories of the soldier system. Source: Doney, 1996.

The Army's acquisition of systems is normally accomplished in phases. During the engineering and manufacturing development phase, the contractor seeks to meet objectives with prototype systems until a final system design is approved by the Army Project Manager. The next phase is the production and fielding of systems built to final design specifications. To accelerate the fielding of Land Warrior, an open, modular system design has been adopted, which allows for advanced subsystems to be inserted into fielded versions of the ensembles after they are developed by the Natick RDEC.

Candidate subsystems to be developed and inserted into the Land Warrior design have already been identified and are listed in Figure 2-2. Higher priority improvements slated for insertion include a wireless weapons interface, integrated sight, integrated navigation, enhanced soldier radio, system voice control, combat identification functional integration, and an upgraded helmet-mounted display. Lower priority enhancements being considered for development include a hand-held color display, a head orientation sensor, and interfaces for a personnel status monitor, a portable mine avoidance device, and a chemical agent detector.

The Army provided the committee with estimates for power requirements of subsystems approved for the Land Warrior system, as well as for several subsystems being considered for insertion. These power requirements (listed in Table 2-1) provide a baseline for comparison with achievable future systems for the dismounted soldier. The Land Warrior design assumes that standard military batteries will be used as the energy source for all of the subsystems.

Table 2-1 shows that the computer in the computer/radio subsystem has the largest power requirement, followed by the two radios. In spite of this, neither a more energy-efficient computer nor an advanced terminal, which might consolidate the functions of computer and radio, is being developed for insertion into the Land Warrior system. The committee also noted that the general-purpose personal computer architecture on which the soldier computer is based has much more computational power than necessary to accomplish the specified functions; presumably the extra power will be available for added functions and capabilities. The Natick RDEC is considering an advanced computer architecture as a possible "revolutionary operational enhancement" to Land Warrior in the future, but implementing it would require deviating from the Army's approved command, control, communications, computers, and intelligence (C^4I) technical architecture (Army, 1995).

The Land Warrior system was designed to meet the operational requirements of the dismounted soldier as defined by the Infantry Center in a detailed Operational Requirements Document (TRADOC, 1994a). The Infantry Center estimated power requirements for each of the Land Warrior capabilities by compiling "operational mode summaries" for a variety of typical missions. The process used to estimate power requirements for the laser rangefinder capability is described in Appendix B. The Land Warrior system design will undoubtedly change in the near term in response to new requirements identified for Force XXI operations on a digitized battlefield.

IMPACT OF DIGITIZATION

The Army Digitization Master Plan defines digitization as "the application of information technologies to acquire, exchange, and employ timely digital

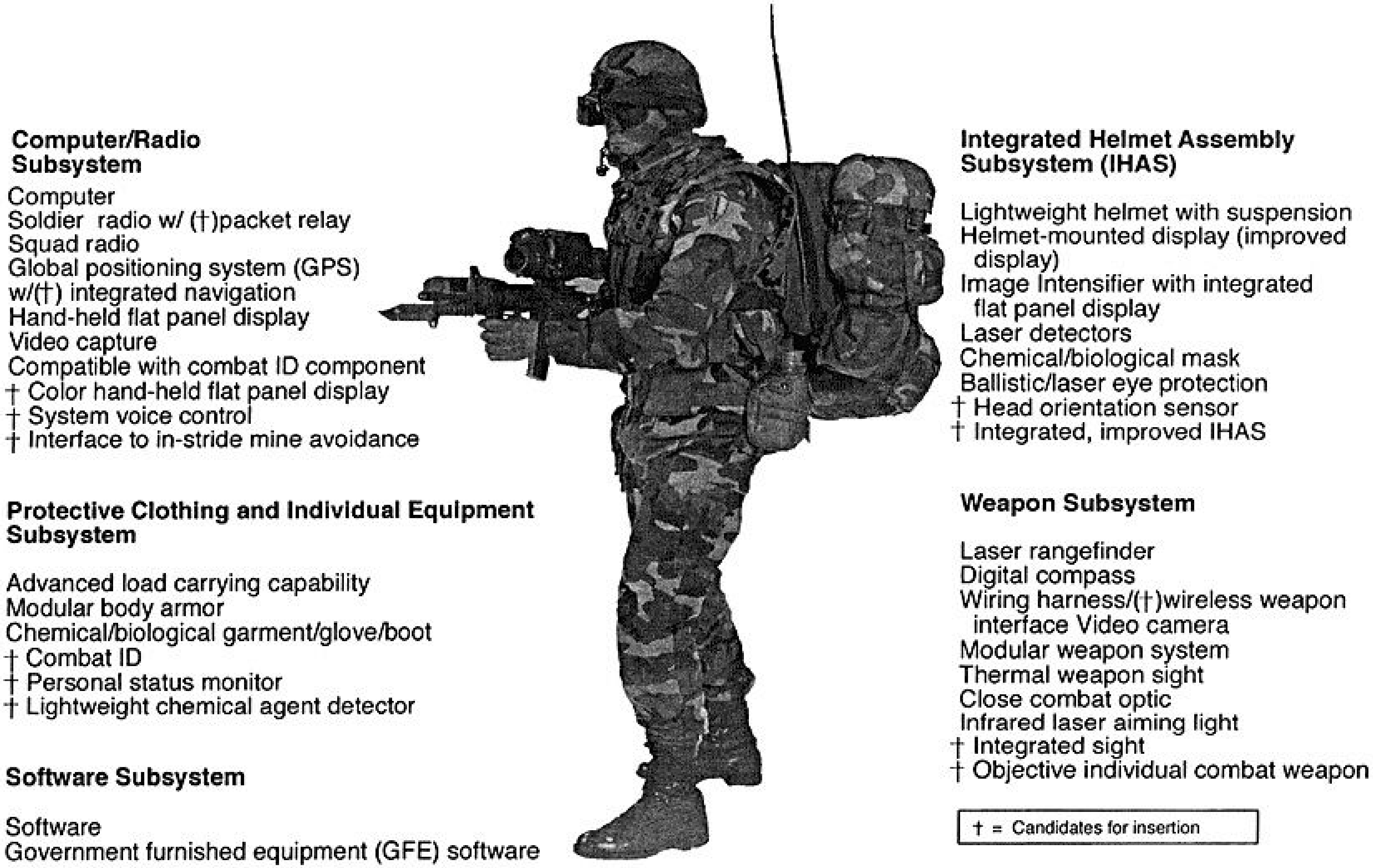


FIGURE 2-2 Land Warrior subsystems. Source: Doney, 1996.

TABLE 2-1 Power Requirements for the Land Warrior System

	Functional Operating Power (W)
Computer/Radio Subsystem	
Computer	14.800
Hand-Held Flat Panel Display	6.400
Soldier Radio	
Receive	1.400
Transmit	6.000
Squad Radio	
Receive	2.000
Transmit	12.000
Global Positioning System	1.500
Video Capture	1.000
Subtotal	45.100
Integrated Helmet and Sight Subsystem (IHAS)	
Laser Detectors	0.600
Helmet-Mounted Display	4.900
Imager	0.100
Subtotal	5.600
Weapon Subsystem	
Laser Rangefinder	0.050
Laser Aiming Light	0.075
Digital Compass	0.350
Thermal Weapon Sight	5.525
Subtotal	6.000
TOTAL	56.7

information throughout the battle space, tailored to meet the needs of each decider (commander), shooter and supporter … allowing each to maintain a clear, accurate vision of the surrounding battle space necessary to support both planning and execution" (Army Digitization Office, 1995). Digitization is the horizontal and vertical integration of operating systems on the battlefield to create an interlocking network for exchanging information. This network allows friendly soldiers to have a common picture of the battle space that includes information on both enemy and friendly situations in near real time. Ideally, the high-speed data exchange will correlate, fuse, and display intelligence information at all levels.

For the first time, a shared vision of the battle space will allow soldiers at all levels to visualize operations simultaneously (TRADOC, 1994b). Thus, the dismounted soldier will be more empowered than ever before to take independent action.

Digitization provides for the evolution of technology on the battlefield, and operational concepts must be developed to ensure that new tactics and doctrine make effective use of information technology. Figure 2-3 shows that a change ("delta") in military tactics, techniques, and procedures is produced when doctrine, training, organization, and support systems are enhanced by information technology. Conversely, as the arrows in the figure show, the "delta" also affects the Army's doctrine and operational concepts. Compared to the traditional evolution of military doctrine, digitization represents a revolution in military thinking.

A recent Task Force XXI AWE conducted at Fort Hood, Texas, used prototype computers and radios operating in a "tactical internet." The experiment was designed to study the capabilities enabled by digitization technology and will lead to changes in organizational structures and doctrine for the Army's first "digital" units.

The impact of digitization on the battlefield in general, and on the dismounted soldier in particular, raises two issues. On the one hand, the soldier in

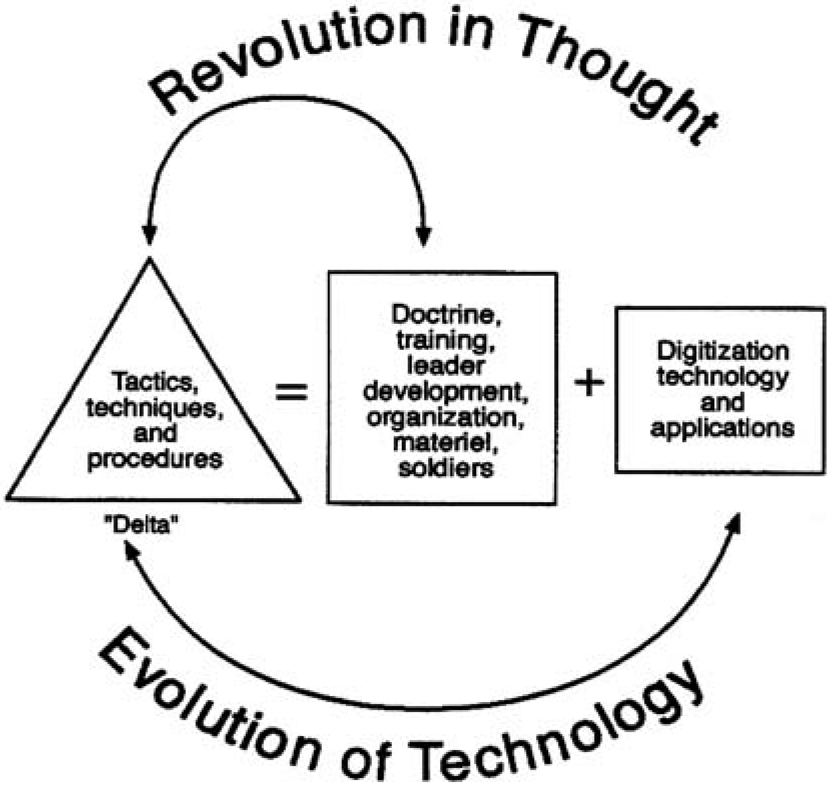


FIGURE 2-3 Model for introducing technology and digitizing the battlefield.

the twenty-first century will have access to data from a variety of battlefield operating systems, which will provide a shared vision of the battlefield and a combination of means to engage the enemy. On the other hand, the soldier's equipment will be heavier because of the new systems themselves and the batteries needed to power them.

The problem of weight has been studied for many years. One of the principal objectives of the Land Warrior program is to reduce the soldier's load (TRADOC, 1994a). A study by the NRC found that the combat soldier was 50 to 110 percent overloaded (NRC, 1993b, p. 20). The Army Infantry Center estimates that an Army platoon radio-telephone operator equipped with a field radio carries just over 150 pounds. The dismounted soldier system tested during the AWE at Fort Hood weighed more than 100 pounds with batteries (Griggs, 1997). The goal for the Land Warrior ensemble is 40 pounds, resulting in a 75-pound "fighting load."

OPERATIONAL FACTORS

Operational factors will determine the amount of energy available and the energy consumption of the Land Warrior system. Many operational factors are products of warfighting doctrine and are inherent, by specification, in the equipment. Other operational factors are determined by battlefield organizational structures, individual soldier operating procedures, and military channels of communications.

Traditionally the Army has assumed that enough power can be supplied to support each operational capability. Therefore, the adequacy of compact power sources has not been a factor in determining warfighting doctrine. But the Force XXI experiment demonstrated that the Army is prepared to change to accommodate new technologies. It is already apparent that the new electronics systems complicate battlefield logistics support by increasing the types and number of batteries required, which makes increasing the energy capabilities of compact sources a necessity.

Rising energy densities and the more detectable electronic signatures of devices, such as laser rangefinders, infrared detectors, computer displays, and radios, also threaten the soldier's survival by increasing his or her electronic profile. The battlefield requirement of minimizing the likelihood of detection by the enemy will become increasingly important as the doctrine for waging information warfare is developed.

Electronics systems used by the dismounted soldier will require that multiple power requirements be satisfied simultaneously. In the Generation II Soldier development program at the Natick RDEC, power was treated as a limited resource, the merits of different battery characteristics were analyzed, and trade-offs between battery and equipment weight were considered. In developing requirements for the Land Warrior system, U.S. Army Training and Doctrine Command (TRADOC) compiled operational mode summaries to establish upper demand and then using those demands to define a specification for the overall system. This system approach also allowed for allocating power among electronic subsystems and, perhaps for the first time, provided a means for the Army to consider energy characteristics in the overall design.

The ideal of developing a single power source to support multiple capabilities has driven extensive efforts to optimize energy storage characteristics and to reduce the number of power sources that must meet the more stringent military standards. Work has been spurred by a growing awareness of the logistical costs of storing, distributing, and disposing of the immense array of batteries that support large-scale operations, such as Desert Storm and unit training at the National Training Center. A recent policy decision to increase the use of rechargeable batteries in order to reduce operational costs has focused even more attention on what is becoming an urgent research priority (AMC, 1996). This decision indicates a growing awareness in the Army that there are limits to the number and variety of systems that can be supported by batteries.

Although new requirements will continue to surface, all but one of the requirements already identified have power requirements of less than 100 W. The one exception is the "cool suit," a proposed system capable of providing microclimate cooling for the soldier in case of a biological, chemical, or nuclear attack. To operate untethered from a power generator, a cool suit would require a new compact source capable of delivering more power than any battery yet developed.

Even with a new compact energy source, probably a fueled source, the Army must find ways to lower the demand side of the energy equation. Power management techniques, both internal and external to electronic subsystems, can increase energy efficiency. External controls can be exercised over the distribution of energy to multiple subsystems. Controls internal to the subsystems, such as "sleep" modes or power regulation software, can also help reduce energy consumption.

Like fuel and ammunition supplies, the energy supply should be considered operationally. Energy discipline, however, is not mentioned in Army doctrine or literature. To all appearances, the Army requires 100 percent operational capabilities, that is, constant communications, continuous distribution of data, and uninterrupted energy supplies for portable equipment. The availability of sufficient energy is taken for granted, and the dismounted soldier has not been conditioned to exercise discipline or restraint in the use of energy during operations or training.

THE ARMY AFTER NEXT

The dismounted soldier outfitted with the fully-developed Land Warrior ensemble is expected to be an integral part of the "digitized" Army of the early twenty-first century. Building on experiments at Fort Hood and the National Training Center, a division of troops will be outfitted with the electronics and other equipment needed for digitized operations, and dismounted soldiers in the first "digital" division will be the first to receive the Land Warrior ensemble. Other divisions will follow, depending on funding for modernization. At the time of this study, 34,000 Land Warrior systems were scheduled to be fielded to Army units by the year 2003. Using past acquisition life cycles as a guide, the Army expects that Land Warrior systems will be in service through the year 2015.

What lies beyond Force XXI? To prepare for the more distant future, the Army is attempting to visualize an "Army After Next" (AAN) to identify strategy, required capabilities, and enabling technologies 30 years from now, focusing on the 2025 time frame. In characterizing the AAN, TRADOC predicts that the art of war as practiced today will remain valid and that revolutionary changes in capability will be brought about by the integration of technology and effective organizational structures. Future organizations will probably be "flatter," that is, "cellular" rather than "hierarchical" (Killebrew, 1996). Because Army requirements for the AAN have yet to be defined, the committee was free to conceive of advanced concepts for providing and using energy in 2025 based on the projections of current trends in applicable technology areas.

Trends in technology can be described from at least two perspectives. The first perspective considers enabling technologies for meeting the needs of the dismounted soldier with soldier systems like the Land Warrior system. Moving forward in time, for example, the most obvious trend is that the percentage of energy required for the computer subsystem will decrease in relation to other subsystems. Other trends upward or downward can be used to project the characteristics of future dismounted soldier systems and to estimate future energy consumption.

A second perspective considers issues surrounding the enabling technologies. For the AAN, TRADOC highlighted four technology trends for 2025, including the following (Killebrew, 1996):

- Procurement agility will become a strategic issue.
- The information revolution will continue, and a "power" revolution is a necessity.
- New sources of battlefield energy will have revolutionary consequences.
- Strategic and operational mobility must be increased.

These trends indicate a trend for Army capabilities and enabling technologies, especially those with the potential to affect electric power for the dismounted soldier.

FINDINGS

The energy requirements of the dismounted soldier are reflected in the power requirements for each Land Warrior subsystem. By analyzing operational concepts for each subsystem, the Army estimated battery requirements for the system. The Land Warrior program does not include the development of an alternative to batteries as an energy source, and subsystems in the ensemble will not have been designed with energy efficiency as the foremost consideration.

Energy requirements for the dismounted soldier will change with the insertion of advanced subsystems as the Land Warrior system design evolves to support operations on the Force XXI digitized battlefield. Evolutionary operational enhancements to the Land Warrior program and revolutionary changes in dismounted soldier operations envisioned for the AAN (after 2025) may add to these requirements.

The committee considers the continuing effort by the Army to realize the full potential of electronics, computer, and information technologies on the battlefield as the primary basis for all future power requirements. This means that the dismounted soldier will require more than improved energy storage. Future soldiers will require a combination of energy sources and energy drains that will extend the range and duration of operations with substantial reductions in weight and bulk. At the same time, new sources and systems must not make the dismounted soldier more vulnerable to detection by the enemy. The Army has traditionally considered electric power for the dismounted soldier as an inexhaustible resource, but the growing number of portable electronic systems and the associated battery requirements have motivated the Army to investigate energy-efficient technologies that will increase energy availability and reduce demand.

3

Energy Sources and Systems

The highly mobile and automated Army of the future will rely on an increasing variety of "smart" ordnance and equipment. Technological sophistication, however, will be accompanied by the need for advanced energy technology formatted for particular users. Battery type, fuel type, autonomy time, absolute power, reliability, commonality, and the cost of power systems will shape the battlefield as much as advances in communications, computing, sensing, lethality of weapons, and protection.

Numerous studies have recognized the need for major advances in battlefield power technology (Space Power Institute, 1990, 1992a, 1992b, 1994). Mobility for the dismounted soldier demands energy storage density in a compact package that can satisfy power requirements of up to 100 W. In addition there is at least one requirement for more than 100 W to support a microclimate cooling suit that would ensure a modicum of comfort under biological, chemical, or nuclear attack. New energy sources and systems must meet these requirements without increasing the vulnerability of the dismounted soldier to detection by the growing array of sophisticated sensors on the battlefield.

The basic types of military energy systems have not changed appreciably since the Second World War. The motor generator and the battery are still the primary sources of energy on the battlefield. Batteries are the workhorse of energy storage for the dismounted soldier and have improved steadily through the years. But they have reached the point at which improvements of more than a factor or two in most critical parameters cannot be made safely. Using new materials and chemistries, batteries are approaching explosives in terms of energy density. Hence, safety is now an issue from the perspectives of both storage and usage. Other long-standing issues related to using batteries in large-scale military operations are cost, reliability, maintenance, and availability.

Equipment for the dismounted soldier must be both compact and rugged. Availability of fuel, specific energy, specific power, minimal signature (electronic, thermal and acoustic), simplicity of operation, and environmental impact are also major considerations. The mass a soldier can carry on a mission is already approaching its limits forcing a trade-off of bullets or food for batteries to power electronics.

Advanced power technology is multidisciplinary. The ultimate utility of a particular technology may depend not only on the fundamentals of the device itself, but also on the electrode technology or the availability of the fuel needed to power it. As a consequence, the Army is exploring ways to manage and increase mission times utilizing whatever technology can be invented. Any reduction in energy demand for the same capability immediately translates into increased mission time for the same mass or the same mission time with reduced mass. The Army can optimize its use of energy and power by:

- employing more energy-dense power sources
- using systems optimized for minimal energy and power requirements
- maximizing the use of available energy (e.g., use of automated controllers and chargers that carefully meter energy and place noncritical functions in sleep mode while maintaining power for critical functions)

To date, fueled energy systems are low in specific energy and specific power except when they are used for long run times when fuel mass dominates system mass. Scaling to small sizes is only now being understood. Recent advances in fueled technologies, such as proton exchange membrane (PEM) fuel cells, thermophotovoltaics, alkali-metal thermal-to-electrical converters (AMTEC), and microturbines, appear to be capable of producing higher specific energy and specific power than the fueled systems currently in use (motor generator sets). Furthermore, these technologies appear to maintain their favorable characteristics when they are scaled to small sizes.

A technology that can be deployed in the field rarely has the same capabilities as laboratory prototypes or theoretical models. Some obstacles are fundamental, but some can be overcome through appropriate research and development (R&D), innovations, and skillful engineering. The power level of a fueled system is determined solely by the converter. The specific power of a converter decreases with the addition of fuel, in direct contrast to a battery, in which the specific power stays constant as energy is added.

The use of a fueled system does not eliminate the need for intermediate storage because fueled systems cannot operate when they are submerged unless they carry a stored oxidant. The intermediate store must also be rechargeable. Of the numerous choices for intermediate storage, only the ones most relevant to the dismounted soldier are discussed in this report.

Figure 3-1 lists the range of storage media available for consideration within the framework of this study. Note the enormous difference between energy sources based on the chemical bond and those associated with the nucleus. Although there are political, safety, and technological barriers to using nuclear energy to provide or store power for the dismounted soldier, the committee could not ignore its vast potential. Human- powered systems used by some foreign armies and by U.S. special forces were also considered.

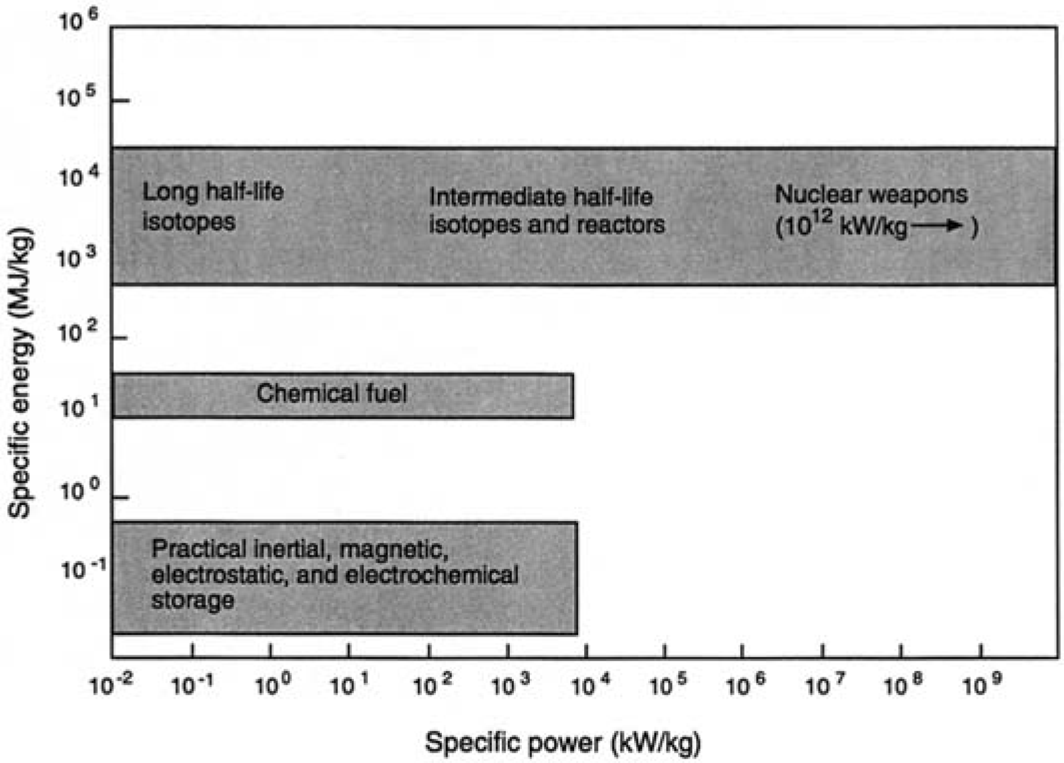


FIGURE 3-1 Specific energy and specific power for various energy storage media. In general, the higher the specific power, the lower the specific energy. Note that 1 MJ/kg is equivalent to 277 Wh/kg.

The committee investigated some technologies that are not discussed in this report because they would be inconsistent with soldier mobility requirements and thus not good candidates to support future dismounted soldier systems. For example, the large masses associated with containers and cyrogens needed for inductive energy storage (possibly including superconductors) would restrict soldier operations. Similarly, thermal storage and conversion of waste heat, while technically feasible, would require "phase change material," which would add to the mass burden.

Detailed descriptions of the energy and power systems surveyed in this chapter are contained in Appendix C. Table 3-1 summarizes their characteristics. For each system, the table includes assessments of the state of the art, the potential for improvement, key issues, scaling laws, the impact on dismounted soldier operations, hostile signature and suppression potential, fuel requirements, and autonomy time.

Every system included in Table 3-1 has some drawbacks. For example, recent advances in the development of hybrid power systems with a fueled system

TABLE 3-1 Technology Summary of Energy Systems

Power System	State of the Art	Potential for Improvement	Key Issues	Scaling Laws	Impact on Dismount Soldier	Hostile Signature	Suppression Potential	Fuel Required	Autonomy Time
Primary battery	Mature	Moderate	Energy density Safety Power density Environmental impact	Known	Longer mission Less weight Disposability	Minimal	Excellent	None	Hours/days
Secondary battery	Mature	Moderate	Energy density Cycle life Power density	Known	New capability Cost savings Less weight	Minimal	Excellent	None	Hours
Thermophoto voltaics	Emerging	Excellent	Requires cooling Efficiency Lifetime Ruggedization	Uncertain	New capability Cost savings Longer mission	Thermal	Moderate	Multifuel	Days/weeks
Fuel cells (hydrogen)	Exploratory development	Excellent	Fuel Water management Safety	Known	New capability Less weight Cost savings	Thermal	Excellent	Hydrogen	Days/weeks
Fuel cells (methanol)	Emerging	Excellent	Fuel and fuel crossover Catalyst	Uncertain	New capability Cost savings Less weight	Thermal	Excellent	Methanol	Days/weeks
Alkali-metal thermal-to-electrical converters	Emerging	Excellent	Liquid metal Membranes Pumps/wicks Ruggedization	Uncertain	New capability Less weight Cost Savings	Thermal	Moderate	Multifuel	Days/weeks
Nuclear isotope	Limited	Excellent	Safety Environmental impact Cost Public acceptance	Known	New capability Autonomy	Thermal Nuclear	Moderate	Special	Month/years
Internal combustion	Some versions mature	Moderate to excellent	Fuels Vibration Life	Uncertain	Cost savings Less weight	Thermal Acoustic	Moderate	Multifuel (Some special)	Days/weeks
Microturbine	Emerging	Excellent	Safety	Uncertain	New capability	Acoustic	Difficult	Special	Days/weeks
Thermoelectric	Some versions mature	Moderate to excellent	Efficiency Materials Coupling	Known	New capability Less weight	Thermal	Moderate	Multifuel	Days/weeks
Human-powered	Nonexistent	Excellent	Conversion mechanisms	Unknown	New capability Cost saving Autonomy	Minimal	Excellent	Food	Weeks

for primary energy storage could be revolutionary for the dismounted soldier but may require alternative (nonlogistic) fuels for use on the battlefield. Primary batteries cannot provide the requisite mission energy for the energy budgets projected today without creating a significant safety hazard. Primary batteries also pose a significant environmental hazard, which is likely to increase as newer chemistries become available. The main hazards for batteries are explosive rupture, toxic and corrosive electrolytes, and environmental pollution (if they are not recovered). Inevitably, there will be trade-offs among safety, energy, and power, which must be carefully considered for each system and mission. It would be highly desirable for soldiers to have a secondary battery with the specific energy and specific power of current primary batteries. This would lessen environmental impact because the need to recycle them would be less frequent. Even a high specific energy rechargeable battery with limited life, say 50 charge/discharge cycles, would greatly relieve supply problems and ease the problem of ultimate disposal.

Any system energetic enough to be considered a major advance for the Army will undoubtedly also be dangerous. Batteries are both energy storage systems and converters in the same units. Batteries require that the oxidant and reductant be in close proximity. In fueled systems, the energy dense fuel is in a separate enclosure. Except for fueled systems that use hydrogen as a fuel, they use rather involatile fuels, which can burn rapidly but will probably not explode. The fuels themselves are housed in external tanks, which could be subject to penetration and subsequent burning if the penetrant were energetic enough to cause ignition.

Primary batteries will be used in military systems for the foreseeable future, but they will also continue to present problems with disposal, inventory, safety, and availability. Wherever possible, the Army will replace them. The dismounted soldier will probably ultimately use rechargeable batteries that have higher specific power and energy (which would match or exceed those available from current primary batteries) coupled with "personal" charges. The rechargeable batteries would have enough lifetime for many missions and could be returned to the inventory after recharging. For long missions, the primary store, which is envisioned as fueled storage, could be replenished with fuel, preferably, but not necessarily, a battlefield fuel. All of the fueled systems described in this chapter have the potential for long life and thousands of refuelings. With the exception of microturbines, all of them are at a stage at which advanced development is possible. Coupled with a suitable rechargeable battery with similar cycle capability, these fueled systems would reduce the inventory necessary to maintain readiness. The primary logistical concern would become fuel. The environmental impact associated with the disposal of batteries would also be greatly reduced because fueled systems would not have to be recycled after each mission.

High specific energy rechargeable batteries are also important to commercial industry. It is possible, therefore, that the military battery will become more readily available, guaranteed by the commercial uses of the same technology. Smart chargers, "fuel gauges," and power management techniques will also be forthcoming from the commercial sector. Thus, commercial off-the-shelf (COTS) systems on the battlefield could become the norm rather than the exception.

ALTERNATIVE TECHNOLOGIES

Primary and alternative technologies for meeting power requirements below 100 W are discussed in the following sections. Combined with the detailed descriptions contained in Appendix C, this survey provides a basis for an engineering database of the most promising technologies. Sections include rechargeable batteries, fueled systems, nuclear energy sources, human-powered systems, photovoltaic technology, thermophotovoltaics, electrochemical capacitors, and hybrid systems.

Rechargeable Batteries

Although battery technology is relatively mature (Cairns, 1992; McLarnon and Cairns, 1989), evolutionary changes in practical batteries are likely to continue, even in the long term. In the future, batteries will be safer, last longer, and be predominantly rechargeable. The specific energy of rechargeable batteries will more than double and will approach or exceed the specific energy of the best primary batteries. Lithium chemistries are the most energetic and will continue to be pursued in both the commercial and military sectors (Arthur D. Little, Inc., 1996; Megahed et al., 1994). Rechargeable lithium polymer batteries are being actively developed by both sectors because they promise both high specific energy and high specific power. Laboratory prototypes have specific energy on the order of 200 Wh/kg and specific power on the order of 200 W/kg. The growth potential in practical features for these technologies is a factor of two or more, but safety will be an issue. The number of charge-discharge cycles for the laboratory prototypes is approximately 300, with growth potential to 600 or more. The environmental issues associated with lithium chemistry will remain, however, and prices will be high as long as the civilian market for them is small. Coupled with a charger system, rechargeable lithium batteries offer enormous potential for the Army.

Major improvements (more than 20 percent) in the battery and hybrid systems discussed in this chapter can be achieved by improving processing technology, active material composition and morphology, reinforcing components, electrolytes, and key components that limit cycle life and cycle rate, such as separators.

Fueled Systems

Fueled systems, which are in various stages of development, have the potential to replace or augment batteries in the Army inventory. For energy requirements greater than about 1 kWh, fueled systems offer a clear mass advantage (see Appendix C). Their fuel costs are several orders of magnitude lower than those of the current primary batteries, and they are less harmful to the environment. In addition, fueled systems are reusable and can generate continuous power with refueling. Using small fueled systems may require a new battlefield fuel, such as hydrogen, methanol, propane or natural gas. Using hydrogen or methanol would eliminate or drastically reduce the need for primary batteries and would also produce drinkable water.

Fuel Cells

Enormous progress has been made in the development of small fuel cells that can replace batteries in some applications (Courtesy Associates, 1990, 1992, 1994, 1996; Kinoshita and Cairns, 1994, Kinoshita et al., 1988; Gottesfeld et al., 1995). Fifty-watt hydrogen PEM fuel cells with a form factor the same as that of the Army BA-5590 battery have been built and demonstrated. Recently, a similar fuel cell was built to fit in the battery cavity of a standard Army field radio. In addition to silent operation and minimal thermal signature, this fuel cell is free of the logistics chain associated with primary batteries because it uses hydrogen, a fuel that can be obtained directly or indirectly from many source materials. The principal by-product of hydrogen fuel cells is water. Several demonstrators with power levels of 50 to 300 W are being evaluated in the field.

Figure 3-2 illustrates the relationships between fuel cells and batteries. The fuel cell is not a viable candidate in terms of specific energy for mission energies less than about 0.75 kWh. For these low-energy missions, the battery is still preferable because of the irreducible mass penalty for the fuel cell converter. However, most missions described by the Army for the Land Warrior ensemble require energy greater than 1 kWh. For very high energy missions, fuel cells can provide an order of magnitude improvement over the comparable mass of batteries because only the mass of the fuel expended needs to be added to increase the available energy. The fuel cell technology shown in Figure 3-2 is state of the art. Expected improvements in fuel storage and the introduction of methanol fuel cells promise to increase the specific energy of fuel cells.

The single most important problem with the deployment of fuel cells is the need for hydrogen as a battlefield fuel. The decision to use a new fuel on the battlefield will depend on the savings in the reduction of, or elimination of, the need for primary batteries, which now perform the same function. There are several ways to produce hydrogen for battlefield use. Reformers are available for the JP fuels, methane, propane, butane, and natural gas, all common, readily obtainable fuels from commercial sources. Hydrogen can be stored in hydrides and produced by chemical reaction. It can also be stored either as a compressed gas in high pressure tanks or as a liquid at cryo temperatures.

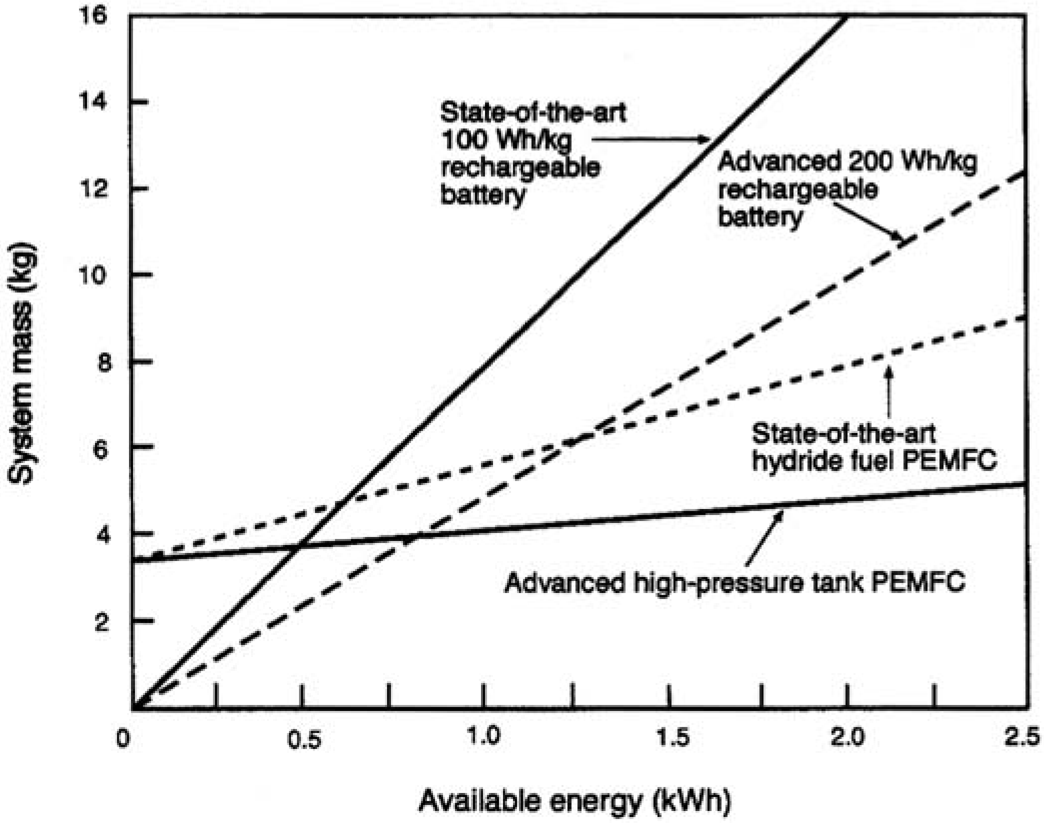


FIGURE 3-2 Graph showing the "crossover" points for battery and fuel cell power systems as functions of available energy and system mass. The assumed system power level is 50 W. PEMFC is proton exchange membrane fuel cell.

The development of advanced fuel cells that oxidize methanol directly is progressing. Current efforts are focused on the development of membrane materials that will dramatically reduce the tendency for methanol to cross the membrane (fuel crossover decreases efficiency and limits the life of the device). The power density of direct methanol fuel cells is lower than optimal for military applications. Excellent progress is being made toward solving both of these problems. In terms of technology demonstration, direct methanol fuel cells are three to five years behind the hydrogen-fueled PEM fuel cells. Current laboratory cells are approximately 35 percent efficient and have demonstrated modest life. Efficiencies as high as 45 percent are projected. Methanol, which is only about one-sixth as energy dense as hydrogen, also produces drinkable water and carbon dioxide gas. Methanol is liquid at room temperature and can be readily manufactured from coal, natural gas, and wood by-products. The current cost of methanol is about 40 cents per gallon.

Heat Engines and Electromechanical Energy Converters

Options for converting the energy stored in fuels to electricity include fuel cells, thermoelectric and thermophotovoltaic sources, and heat engines with electromechanical energy converters. Of these options, conventional heat engines represent the most mature technology, with high converter operating efficiencies and power densities (Space Power Institute, 1992b). An unconventional microturbine system in the very early stages of development also holds significant promise (Tan et al., 1997).

Heat engines can be classified in a number of ways, but perhaps the distinction between internal and external combustion engines is the most appropriate discriminator for the dismounted soldier. Both convert the heat of combustion of an appropriate fuel to mechanical energy in the form of a rotating or oscillating shaft. This mechanical energy can, in principle, be converted to electrical energy by either rotating or reciprocating electrical generators with magnetic or electric fields. In sizes appropriate for the dismounted soldier (50 to 250 W), internal combustion engines are the most mature heat engine technology. The impulsive nature of thermodynamic energy conversion, however, leads to noise and vibration problems, as well as difficulty in reliably restarting on demand.

Efforts are under way to produce a microturbine technology by applying microfabrication technology to the development of a gas microturbine that can be used as a compressor or as a driver for an alternator. This project, which is based on fabrication techniques for silicon-carbide microelectronics, promises economical microturboalternators with high specific power. By 2015, prototype microturbines machined from silicon may have been developed, which will provide 1,000 Wh in a package weighing as little as 0.25 kg. If this high risk effort is successful, it would provide extremely attractive specific power and energy for the dismounted soldier. Potential problems associated with heat engines include difficulties of starting, thermal and acoustic signatures, vibration, the generation of toxic or hazardous combustion products, and the inability to operate in all orientations or to operate under water (without air).

Thermoelectric Conversion

Thermoelectrics technology is mature and has been used in numerous space applications for power and a broad array of applications for cooling, in both the civil and military sectors. Thermoelectric generators use the Peltier effect to produce electricity from any heat source (Rowe, 1988). The efficiency of these devices is determined by the temperature of the heat source, the rejection temperature, and the materials comprising the thermoelectric elements. Thermoelectrics is a mature and proven technology, and thermoelectric devices are extremely reliable (years in space), have few moving parts, and are inherently silent. At present, the maximum efficiency attainable from thermoelectrics is on the order of 8 to 9 percent in a laboratory device. The efficiency is less than 5 percent in practical situations. Advanced programs are researching new materials that could improve the efficiency for practical power systems to 10 percent. The commercial infrastructure is in place to manufacture and market large thermoelectric units for remote applications. The maximum power levels for these units are on the order of 100 W. Thermoelectric power systems are capable of using standard Army multifuel. A 500 W unit was projected to weigh 20 kg unfueled and to have an efficiency on the order of 9 percent (Bass et al., 1994). Although thermoelectric power systems are silent, they do have substantial thermal signatures.

Alkali-Metal Thermal-to-Electrical Energy Converter (AMTEC)

The "sodium heat engine," or AMTEC, is capable of converting thermal energy from any heat source to electricity with estimated efficiencies as high as 35 percent (Ivanenok and Hunt, 1994). In the last decade, much progress has been made in the development of the relevant materials technology and in understanding the basic physics of single cells. Serious efforts have been made worldwide to reduce the technology to practice. Civilian applications in automobiles, self-powered home gas appliances, and space power have been investigated. The most interest is being shown at present in using AMTEC for deep space probes where the heat source is nuclear.

The principle of energy conversion used in the AMTEC is independent of the heat source and, because modest laboratory efficiencies have been obtained, it is a good candidate for Army applications in the 50 to 500 W range. Power sources using AMTEC are multifuel-capable, and scaling to small sizes is reasonably well understood. Like all fueled systems that are combustion driven, AMTEC ejects the thermal energy that is not converted at a relatively high temperature. AMTEC cells use liquid sodium in the energy conversion process. The amount per cell is less than one gram and is usually confined to a wick structure. NASA has chosen AMTEC as the conversion mechanism for the "Fast Pluto Flyby" spacecraft power system. In laboratory cells, reliability has been demonstrated to thousands of hours, and laboratory efficiencies of 20 percent have been recorded.

At the single cell level, AMTEC converters are well understood. The primary outstanding technical issues are:

- long-term materials degradation and poisoning of the alkali-metal loop
- techniques for effectively and efficiently making parallel and series arrays that minimize heat loss
- efficient external liquid combustion and recuperation in small systems
- system demonstrators

Nuclear Energy Sources

Nuclear energy sources are capable of more than 1,000 times the energy density of energy sources based on chemical bonds (see Figure 3-1) (Space Power Institute, 1992c). However, releasing nuclear energy in a controlled way is extremely difficult. Because of possible health and environmental hazards, the problems inherent in using nuclear materials on a battlefield are formidable and could only be addressed in a large and expensive program. This is unfortunate because deep space probes using nuclear sources have demonstrated lifetime and reliability characteristics far exceeding those of other energy sources. Nuclear power sources could extend autonomy time to months or years instead of hours.

Nuclear isotopes offer the most potential for Army applications. The energy density of radioisotopes is enormous, and they are extremely cost effective per watt-hour delivered. The fundamental physics of isotope-powered systems, however, dictate that the production of energy by an isotope cannot be turned on and off; once the isotope is manufactured, it begins decaying. This circumstance places interesting constraints on the shelf life and fuel infrastructure necessary to maintain readiness. Isotope systems are extremely reliable and have been the system of choice for deep space probes. (Indeed, they have made them possible.) Except for a few isotopes, massive shielding is necessary to protect biological systems that must survive in close proximity to the devices. Several small units designed for miniprobes of the lunar and Martian surfaces may in fact be of interest to the terrestrial power community. These innovative designs may be mass and volume efficient because fuel would not have to be encapsulated to survive inadvertent reentry. Other innovations in insulation, such as a proposed modified radioisotope thermal generator (MOD-RTG) for space applications, can also provide important mass savings. Miniature heat engines, such as Stirling, AMTEC, and thermophotovoltaics (TPV), some with efficiencies as high as 30 percent, could be used terrestrially with the possibility of repair and replacement. High efficiency reduces the need for nuclear materials.

Power systems based on nuclear isotopes have been niche technologies confined primarily to space probes, underwater power systems, and use in remote terrestrial locations. Nevertheless, there is a long list of potential applications for isotope systems if sufficient material were available at a reasonable cost and the public bias against the use of nuclear materials could be overcome. The best systems have specific power on the order of 8 W/kg and specific energy greater than 100,000 Wh/kg.

Although the specific energy of a nuclear source is phenomenal, the specific power is poor. Efficient thermal converters, such as the AMTEC, could improve specific power. "Self-powered chips," in which the power levels are relatively small and the amount of radioactivity per chip is as low as a home "smoke detector," are also being investigated.

Outstanding technical issues deal with system studies rather than fundamental research. The Army should keep informed of developments in nuclear technologies, including high efficiency converters and fuel technologies and "beta voltaic" systems intended for integration on microchips.

Human-Powered Systems

Using human powered systems to meet Army power needs may appear to be new and innovative, but human-power has been used for electrical/mechanical systems for decades (Starner, 1996). The hand-cranked portable generator used by Army Special Forces is a good example. Another example is the small "flashlight," which is energized by squeezing a lever. For purely mechanical conversion, the Apollo astronauts took with them to the moon a rotary shaver that had a small flywheel energy store, which was activated by pulling a cord. It is possible to generate up to 100 W in this fashion. Devices of this type are not passive, and they effectively immobilize the individual while power is being generated. Except for the references cited in Appendix C, there does not appear to be any research aimed at exploiting the energy associated with body motion by converting it to electricity.

It is possible through sophisticated energy management and through low power electronics to reduce the dismounted soldier's demand for energy to a level at which it may be possible for the soldier to produce enough electrical power to provide a substantial amount of the electrical energy he or she needs. This would require converting to electricity some of the energy expended by the soldier during everyday activities. The human body stores an enormous amount of energy. The average person consumes between 2,000 and 3,000 calories per day, which is the equivalent of approximately 2,200 to 3,300 Wh. Clearly the amount of energy consumed by an individual is sufficient to power electronic devices if a suitable method could be found for converting a small fraction of that energy to electricity.

Moving the limb and striking the heel while walking or running are potential sources of power, as long as the energy requirement is only a few watts. But physical activity is intermittent, so there would have to be a storage mechanism. Rechargeable batteries, electrochemical capacitors, pneumatics, springs, and flywheels are candidates discussed in Appendix C. And conversion of human power to electricity would still require a generator of some sort. Although the idea is intriguing, at present it is impossible to estimate system performance in units such as Wh/kg and W/kg. This is an area for further research.

Photovoltaic Technology

Like many of the technologies discussed in this report, photovoltaics are mature in many applications and have been used in the commercial domain for many years (IEEE, 1996). Specialized space applications use more efficient cells than those widely available on a commercial basis. But the cost of these cells is orders of magnitude higher than the cost of cells generally available. Photovoltaics are also already being used by the Army.

At the earth's surface, the power incident from the sun is on the order of one kilowatt per square meter of surface. Conversion at a modest efficiency rate makes this a major energy source that is "there for the taking." The successful harvesting of solar energy depends on the development of a viable, affordable photovoltaic cell technology. In general, costs in dollars per watt have precluded large scale commercial exploitation, although the U.S. Department of Energy has funded large demonstration projects capable of producing megawatts of electrical power.

One problem with photovoltaic technology is that the systems can produce power only in daylight and only on clear days. Furthermore, for optimal production, units must "track" the sun. The Army currently uses solar battery chargers in desert operations. These arrays can be folded and can produce enough power to charge several batteries. Several thousand solar battery chargers were used in the Desert Storm operation. Planar arrays with specific power as high as 60 W/kg have been produced for space applications. In general, the conversion efficiency is a function of the cell type and ranges from 10 to 30 percent.

Systems studies of photovoltaic chargers could lead to the development of personal chargers, in appropriately sunny climates, that would function like fueled systems. The following issues are still outstanding:

- bandgap tailored photovoltaics that could function with both artificial light sources and sunlight
- manufacturing technology that would reduce costs
- innovative system demonstrators

Thermophotovoltaics

Recent advances in the technology associated with TPV (thermophotovoltaics) suggest that power systems can be built that range from a few watts of power to more than 500 W (Benner et al., 1994, 1995). Improvements in photovoltaics and emitters, in terms of reliability, size, weight, and energy efficiency, will translate immediately into increased capability and, perhaps, lower cost. TPV is a multidisciplinary technology. For example, solid-state converters must be combined with a radiant element, which is heated from a fossil-fueled combustion source. Recovering the energy remaining in combustion gases is vital for efficiency.

The utility of TPV may depend not on the fundamentals of the device itself, but on whether it can be mass produced from affordable materials, whether it can be made robust and reliable enough to function in a hostile environment, whether it can be engineered into a package with minimal signature, and whether it will enhance the capability of soldiers in the field.

The emphasis to date has been on demonstrating capability, materials, and processes for laboratory devices. Packaging, which is only now being addressed, should clarify many of the obstacles that must be overcome before devices that can be put in the field are possible. Very little attention has been paid so far to demonstrating full systems or establishing engineering parameters, such as figures of merit. Performance specifications and the range of parameters for each component are not known. Efforts to establish an infrastructure are emerging. Major potential applications in the military are auxiliary power units (APUs), battery chargers, and direct battery replacement. TPV technology is available to build systems with efficiency values on the order of 10 percent, and the most optimistic projections for efficiency values are on the order of 30 percent. Until more emphasis is placed on recuperation, however, it is not possible to predict the specific power with any degree of confidence. But specific powers greater than 100 W/kg appear to be reasonable.

Electrochemical Capacitors

Traditional capacitors, in general, have high specific powers but are incapable of high specific energies. Conversely, batteries have high specific energies but are incapable of extremely high specific powers. For many applications, a power source must have the best attributes of both, that is, high specific energy and high specific power. In recent years, classes of devices called "electrochemical capacitors" have emerged that have some attributes of both batteries and capacitors (Florida Educational Seminars, 1996). In specific power and specific energy, they fall between classical batteries and capacitors. They have specific energies on the order of 10 to 20 percent of "good" batteries, and specific powers at least an order of magnitude better than conventional batteries. Compared with conventional capacitors, they have specific power an order of magnitude lower but specific energy an order of magnitude higher.

Although commercial electrochemical capacitors are already on the market, none to date has the requisite internal parameters appropriate for the communications systems envisioned in this report. With successful development of the technology, energy use may become more efficient; pulsed digital communications can reduce the demand for energy while increasing the life of a primary battery or the time between recharges for a secondary battery.

Laboratory prototypes of electrochemical capacitors that can meet many of the criteria for battlefield use have been produced, but they are handmade, and the technology for mass producing them with acceptable and reproducible results has yet to be developed. The technological issues that must be resolved before electrochemical capacitors can be successfully integrated into the electronic devices envisioned for the future Army are listed below:

- understanding the physical phenomena limiting the specific energy, specific power, internal series resistance, internal parallel resistance, degradation mechanisms, temperature dependent phenomena, and the productive life time of electrochemical capacitors

- development of a series of laboratory prototypes for evaluation in hybrid power systems
- development of high-voltage electrolytes
- development of low cost materials for use in both chemical double layer capacitors and pseudocapacitors

Hybrid Systems

In the future, hybrid power sources are likely to be the "technology of choice" for providing power and energy for the Army. Hybrid systems combine the advantages of very high specific energy sources capable of maintaining the base load with very high specific power sources capable of providing peak power when needed. This configuration will greatly enhance power and energy capabilities and will require small portable package. Hybrid systems can be used for everything from personal battery chargers to replacements for conventional field generators.

Digitization places special demands on the power systems envisioned for the dismounted soldier. The best digital transmission is pulsed, requiring higher peak powers in times of battle. The demand for energy is cyclic. But it is the exception rather than the rule for a power source to have both high specific energy and high specific power simultaneously. To ensure that adequate energy is available for the worst case, power system designers typically size systems to meet the maximum demand. As a result, either systems are heavier than necessary or mission planners may be forced to shorten missions or resupply the prime energy source for a given mission. If there are large differences between peak and average demands, it is advantageous to combine a high specific energy, low-specific-power source with a low-specific-energy, high specific power intermediate store. This "load leveling" would enable the soldier to meet the demand with substantial mass savings or longer operational times for the same mass.

Many possible hybrid systems are discussed in detail in Appendix C. In general, fueled systems with rechargeable batteries for the intermediate store are extremely promising. The fueled system could provide long-term average power with a high specific energy rechargeable battery, thus providing higher power levels for hours at a time. Lithium polymer batteries coupled with fuel cells appear to be a particularly attractive combination, although any of the combinations discussed in Appendix C would be acceptable.

On a shorter time scale, a hybrid system would have to provide short bursts of power for pulsed communications or digital image transmission. A battery-capacitor combination for an energy storage system would exploit the high specific power of a capacitor and the high specific energy of a battery. With this combination, the intervals between peak power deliveries would be reduced from tens of minutes for the fueled-battery system to minutes or less for the battery-capacitor combination. As described in Appendix C, the addition of a capacitor to provide peak power improves performance, increases battery life, and improves low temperature operation while lowering life cycle costs and requiring a smaller, lighter package.

POWER FOR MICROCLIMATE COOLING

In the future, the dismounted soldier may have to function in environments that pose serious biological or chemical risks. The approach to personal protection in these environments is to provide the soldier with an overgarment that presents an impermeable barrier to biological and chemical agents. But an impermeable barrier will also impede the evaporation of perspiration, thereby severely limiting the amount of heat that can be removed naturally from the body. Overgarment protection leads to intense heat stress with even modest activity. A soldier's metabolic heat generation is roughly 100 W at rest and as much as 1,000 W during an endurance march. Therefore, an impermeable overgarment will require some mechanism for removing heat. One solution is to provide the garment with supplemental cooling powered by an external energy store.

A minimal level of cooling requires approximately 300 to 400 W. Numerous technologies have been investigated for the cooling system (Raskovich, 1993). The most promising seems to be a vapor compression/expansion cycle similar to the one used in conventional air conditioning and refrigeration. Cooling based on thermoelectrics is inefficient, costly, and heavy. Improvement by a factor of two or more in thermoelectrics will be necessary before thermoelectric coolers will be competitive with vapor cycle methods. For a modest coefficient of performance for the cooling system, the compressor electrical power needs to be in the range of 100 to 150 W.

Microclimate cooling is the most demanding power requirement for the dismounted soldier. There are three options for delivering energy. The first is heat engines that can directly drive the compressor in a vapor cycle. Heat engines in the form of small internal and external combustion devices have been investigated as a way to provide mechanical energy directly to a compressor. Internal combustion devices could be used, but they have acoustic and thermal signatures and produce significant vibrations. Internal combustion motors that have been investigated were taken from the hobby industry or from commercial garden tools. Laboratory prototypes have had limited success.

The Stirling engine, an external combustion device, is quieter than an internal combustion engine, modestly efficient, multifuel capable, and relatively inexpensive. The primary drawback of the Stirling motor is low power density. The primary advantages of Stirling engines are reliability, low acoustic signature, lower thermal signature, and multifuel capability. A Stirling duplex cooler/generator under construction is designed to produce 100 W of electric power and 300 W of cooling power. The device is in the laboratory stages, and the goal is to produce a device with a mass of 9 kg. The laboratory version is projected to be on the order of 13.5 kg.

The second option is to use the electrical energy from a prime source to drive a motor/compressor for the vapor cycle. The fueled systems described in Appendix C appear to be the preferred method of providing the necessary 100 to 150 W of compressor power. Assuming that maximum cooling is needed for six hours, the energy required would be 0.9 kWh for a 150 W electrical demand. A PEM fuel cell point design is being constructed and evaluated that incorporates an oxidizer to prevent fuel cell contamination by the chemicals. The projected mass for this design is 4.5 kg, not including the motor/compressor and distribution system for the coolant. Doubling the fuel load would increase the time to 12 hours and increase the mass by 1 kg.

A third option is batteries that could drive the motor/compressor. Current primary batteries (with 150 Wh/kg specific energy) would have a mass of about 6 kg for a 0.9 kWh (six hour) mission and approximately 12 kg for a 1.8 kWh (12 hour) mission.

Technology Forecast

In the near term, demonstrators capable of powering the microclimate suit will be produced and evaluated on the laboratory scale. Significant improvements in the mass of the system may be possible with new materials and innovative designs. The mass of the system for 12 hours of cooling should be less than 10 kg.

In the long term, advanced thermoelectrics should make the thermoelectric cooler competitive with vapor cycle coolers. Thermoelectric coolers would have a minimum number of moving parts, generate little acoustic and thermal signature, and would be easily repairable. Power systems to drive the thermoelectric arrays will continue to improve and become much less of a factor in the total system mass. Fuel cells and microturbines are the most likely candidates for powering thermoelectric microclimate coolers.

Key Research Issues

Microclimate cooling presents the most challenging power problem for the dismounted soldier. As mission times increase, the mass of battery powered systems quickly escalates to values not compatible with the soldier's load. Fueled systems offer the best solution to the problem. Outstanding issues are:

- development of high specific power, high specific energy fueled systems
- development of lightweight motor/compressor components
- development of new thermoelectric materials with greater efficiency, lower cost, and lower mass
- improved fuel storage and utilization

FINDINGS

Fueled hybrid systems promise revolutionary advances in providing energy to the dismounted soldier, which can dramatically improve logistics and extend mission times. Several fueled energy sources with greater than an order of magnitude improvement in specific energy (compared to primary batteries) are in laboratory demonstration phases and represent low to moderate risk. Fueled systems must be environmentally robust, be able to operate independently of orientation, use common battlefield fuels where possible, be submersible, and operate automatically. Fueled systems will not eliminate the need for a secondary storage unit.

Except for special cases, fueled systems will be hybrids consisting of a fueled converter, a rechargeable battery, and a second electrochemical store in the form of a high specific power battery or capacitor. Hybrid systems can optimize both power and energy requirements.

No order-of-magnitude improvements in batteries are anticipated. High specific power, high specific energy, secondary batteries, and electrochemical capacitors will be essential for future dismounted soldier systems. Missions of more than 1 kWh will require nonbattery power systems/sources or recharging. Electrochemical capacitors are key elements in hybrid systems.

The Army Communications-Electronics Command (CECOM), Army Research Office (ARO), the Army Research Laboratory (ARL), and DARPA have been active in establishing the feasibility of fueled systems. It is time to move from laboratory components to field trials.

The survey of technologies in this study provides a good basis for an engineering database of promising energy sources and systems technologies. In addition to tracking technology development, a database could be used to develop high fidelity computer models of power/energy systems for use in dismounted soldier simulations. The models could take into account soldier systems parameters as well as load profiles for realistic battlefield scenarios. Given this modeling capability, both conceptual and laboratory prototypes of power systems could be built and evaluated.

4

Low Power Electronics and Design

The dismounted soldier depends on power sources, sensors, navigation aids, displays, data processing, and communications. Communications requires the most power, but substantial energy savings can be obtained by minimizing the power requirements for individual display data processing, and sensing functions. This chapter reviews ways to use advanced electronics technology to reduce energy consumption. It summarizes industry trends and projections and indicates some of the advantages of synchronizing military and commercial electronics to leverage the huge industrial investment.

The growing industrial need for creating, accessing, storing, processing, and communicating information is driven by modern business functions and by the growing demands of consumers for data acquisition, processing, and entertainment. The trend originated with the advent of the electronic calculator, the personal computer, and microprocessor-driven games. Although at first stationary electronics systems were used, the industry has moved toward mobile systems, which require lightweight portable energy sources and equipment. Portable commercial and personal communications and data processing have evolved from crude hand-held instruments and bulky laptop computers to miniaturized cellular telephones and pagers, powerful notebook computers, portable global locating/positioning systems, and numerous entertainment systems. The growing demand for computing, along with declining costs, has led to faster, smaller, more reliable integrated circuits that require less power. The technology accompanying these advances can be incorporated into the soldier's electronics systems to make them more functional and to reduce power requirements.

This chapter focuses on the development of advanced semiconductor circuits with an emphasis on silicon technology. Industry has embarked on a long-range plan to reduce the size and operating voltages of electronic devices and to increase the integration of devices and circuits. The Army can use this same plan to schedule its own electronics goals.

The chapter begins with comments on the design of basic circuits, subsystems, and design aids to minimize power. It reviews the National Technology Roadmap for Semiconductors (NTRS) for technology development. To show that industry goals are attainable, the committee presents its own analysis of the ultimate limits for miniaturization and integration density for silicon circuits. Three representative examples of special support centers, conferences, and studies or programs that can serve the Army as sources of state of the art design and technology information on low power circuits and subsystems are then described. The chapter summary suggests issues the Army should address (1) to ensure that adequate design tools are available for implementing low power circuits and technology, (2) to support industry in following the road map toward continued power reductions, (3) to keep abreast of state of the art technology, and (4) to field technology in phase with industry.

The committee estimates that if the Army upgraded technology at a pace comparable with the pace of industry, it could reduce power requirements by more than a factor of 30 for any given function by migrating from 5V operation to 0.9 V operation in 2004. Additional reductions could be obtained by tailoring circuit architecture and designing for low power.

DESIGN REQUIREMENTS

The commercial push toward smaller, higher performance portable systems for computing and personal communications will ensure that low power device and circuit technologies will be available to meet the requirements of the soldier system. However, to exploit those technologies the Army must take full advantage of advances in commercial technology (including using modules, which permit upgrading system elements to prevent obsolescence), and it must adopt customized and partly customized designs optimized for power (with sufficient performance) rather than optimizing for performance (with acceptable power requirements). A full set of computer-aided design (CAD) tools for estimating and optimizing power requirements does not exist, and developing these tools may require a new U.S. Department of Defense (DoD) initiative.

Digital Guidelines

For complementary metal-oxide semiconductor (CMOS) technology, the dominant digital technology, the approximate power dissipated by a circuit is given by the following expression (Chandrakasan and Brodersen, 1995a):

$$P = A \cdot C \cdot f \cdot V^2 + A \cdot I_{\mathrm{sw}} \cdot V + I_{\mathrm{leak}} \cdot V + P_{\mathrm{ext}} \quad (1)$$

A = percentage activity factor. C = total chip capacitance (farads). V = total voltage swing, usually near the power supply voltage (volts). f = chip clock frequency (Hz). I_{sw} = average short circuit switching current (amperes), current when both p-type metal-oxide semiconductor (PMOS) and n-type metal-oxide semiconductor (NMOS) are on simultaneously during a logic change. I_{leak} =

leakage current (amperes) from substrate injection and subthreshold effects. P_{ext} = power required to drive external loads, such as package parameters, chip-to-chip interconnects, etc.

The total power (P) can clearly be minimized by lowering the total voltage (V). Lower voltages will be a natural result of smaller feature sizes operating at lower voltages. Voltage can be further reduced for fixed minimum geometries. However, device speed decreases dramatically as the voltage approaches the threshold voltage, which is acceptable only as long as performance goals can be met. Threshold voltages can be lowered as long as adequate noise margins are maintained and as long as subthreshold currents do not increase energy dissipation.

Capacitance will also be reduced as feature sizes shrink. The effective capacitance ($A \cdot C$) can be further reduced by modifying the design. For example, because energy is dissipated only during transitions, logic functions can be chosen to minimize transitions. Similarly, logic style (such as static versus dynamic implementations) can be selected to minimize transitions, including the extra transitions or "glitches" caused by timing delays between logic signals.

The second term in the equation ($A \cdot I_{\text{sw}} \cdot V$) results from energy dissipated in the direct current path between V and ground, which exists briefly during switching when the difference between V and the PMOS threshold voltage exceeds the NMOS threshold voltage. Short circuit currents are largest when the rise/fall time at the gate input is much larger than at the output. Currents can be minimized by equalizing input and output edge times.

The third term in the equation ($I_{\text{leak}} \cdot V$) arises from energy dissipated due to leakage current, which has two components. The first is the reverse bias diode leakage on the transistor drains, which, although small for each gate, can have a significant impact on a system that is predominately in the standby state because it dissipates energy even in the absence of switching. The second component of leakage current is subthreshold leakage, which is caused by carrier diffusion between source and drain. These leakage current components are a function of the device implementation, which is affected by the semiconductor fabrication technology.

The first term in Equation (1) ($A \cdot C \cdot f \cdot V^2$) is a measure of the device performance and represents the charge transferred to the circuit load capacitance. For maximum efficiency and performance, the product of $C \cdot f \cdot V$, which is known as the charging current (I_{drive}), should be high. At the same time, the leakage currents should be minimized. The drive current is a function of the supply voltage (V) and the transistor threshold voltage, which is determined by the technology. Although a detailed discussion of the relationship of threshold voltage to I_{drive}, I_{sw}, and I_{leak} is beyond the scope of this report, it should be noted that by tailoring the technology manufacturing parameters, I_{drive} can be increased while I_{sw} and I_{leak} are minimized. Therefore, a simply stated goal for optimizing performance and reducing the power requirements is to maximize the ratio

($I_{\text{drive}}/I_{\text{leak}}$) at the transistor device level. Power loss is minimized by using technologies that allow selecting the transistor threshold voltages, tailoring the transistor drive current to the load, and at the same time minimizing the leakage current. The optimum threshold voltage must balance improvements of the drive current at low supply voltage operation with control of leakage currents. Silicon on insulator (SOI) technologies, including silicon on sapphire with thin silicon conducting layers, can be optimized this way. DARPA has sponsored a number of similar projects on the development of low power circuits (Lemnios, 1996).

System Architecture

Modifications of design and system architectures can also save energy, as appropriate to a given system. For example, gated clocks should be used wherever possible, although they may complicate timing analysis. Some specific algorithms and software are more efficient than others from a power perspective (e.g., Grey's Code can require less power than "two's complement" for specific applications), and power-down routines should be used wherever possible. Logic partitioning and architecture can be chosen to optimize energy savings rather than speed; for example, a carry look ahead adder is fast, but a ripple carry adder may dissipate less energy. Large benefits can be realized by customizing layouts for minimal capacitance. When power is a priority, the capacitance of the interconnect must be considered along with the capacitance of the device. Routing should be kept as short as possible, especially on the most active paths. Full custom circuits are better than standard cell and gate array designs, but they shift more of the burden to the designer and lengthen the design process. Combinations of these techniques or new architectures can minimize load capacitance and standby power and optimize supply voltage for circuit sections.

Significant energy savings can be made by choosing the proper input/output (I/O) and package design. Circuit I/O should be minimized to reduce the number of energy-consuming drivers; in some situations, for example, it is more efficient to recompute data than to retrieve it from off chip. In some instances, computational results can be stored in local memory to minimize energy-consuming external memory accesses. Using multichip modules (MCMs) can also reduce the power required to drive long signal lines. The guiding principle should be that as much of the system as possible should be included in a single package, whether the package is a chip or a module. In general, new packaging techniques will be required to minimize interconnect capacitance for low power applications.

The preceding is not an exhaustive list of the design and architectural measures that can be taken to reduce power requirements. Some of these measures make small contributions when considered in isolation; but when power considerations drive all aspects of circuit and system design, the total savings in the volume and weight of the equipment that must be carried by the individual soldier can be significant. And savings to the Army in the requirements for portable power sources can be enormous.

Analog and Radio Frequency Design

Recent advances in CMOS radio frequency (RF) circuits have demonstrated that circuit building blocks, including entire transceivers (Abidi et al., 1997) can be designed to enable fabrication of mixed analog-digital radios on a single chip. Integrated circuit designs have been demonstrated using 1 µm channel lengths and operating at 900 MHz; 0.6 µm channel length devices can operate in the 2.4 GHz range. Scaling feature sizes to 0.35 µm or less will make possible operational frequencies of 5 GHz. These designs have demonstrated that digital circuits can be fabricated on the same substrate as the RF front end, that there is enough on-chip isolation in a low cost package to guarantee stable operation of a receiver with more than 100 dB of base-band gain, and that the power amplifier, when switched across the full output range, modulates the unlocked local oscillator frequency by about 220 parts per million. A complete noise analysis indicates that the noise level is well below the detector pass-band.

These RF analog circuits have demonstrated the capability of switched-capacitor circuits to handle large signals without distortion, the ability to cancel quadratic nonlinearity in balanced circuits, the use of field effect transistor switches to compute signals at RF, and the large signal swings possible in a transistor with an insulating gate. Advanced RF circuits demonstrate that CMOS circuits can be used in low power, low cost transceivers. The Army could use a mix of digital and analog circuits and still take advantage of the improvements in performance and energy consumption afforded by CMOS technology.

The future design of RF circuits, including transceivers for low power, will follow many of the guidelines used for other types of circuits. Circuits can be turned on only during receive and transmit times to minimize the number of circuits that are powered at any given time. Transmission power and bandwidth can be tailored dynamically to meet specific needs. The lowest practical voltage consistent with noise immunity can be used for each section of the system. Circuits can be customized to use special technologies as required, implementing logic and control in CMOS, for example, while using silicon-germanium (SiGe), gallium-arsenide (GaAs) or silicon on an insulating substrate for special RF circuit modules. In addition, the subsystem design can be customized to meet specific mission requirements.

The SiGe heterojunction bipolar transistor technology (Cressler et al., 1994) combines the performance historically associated with compound semiconductor technologies (such as GaAs) with the integration levels, yield, and cost associated with conventional silicon processing. SiGe transistors can be integrated with advanced CMOS processes because they are more scaleable and easier to manufacture than GaAs. SiGe transistors may also give the Army more flexibility in managing power requirements. The SiGe technology in logic circuits has demonstrated sub-20 ps delays, and individual transistors have exhibited cutoff frequencies in excess of 100 GHz. These high switching speeds can support the RF needs for the soldier's radio communications.

Examples of Circuit Design

Actual circuit designs employ a variety of techniques to minimize power requirements at the system level. For example, to achieve maximum energy efficiency for mobile electronics, a number of voltage levels are usually required from a fixed battery source. Special attention must therefore be paid to voltage conversion circuits. There are several choices of design and type of voltage converter that can minimize the required power. Similar examples can be found for implementing computing circuits, portable telephones and radios, displays, and other systems described elsewhere in this report.

DESIGN AIDS FOR LOW POWER INTEGRATED CIRCUITS

One of the capabilities that has enabled the rapid increase in the complexity of integrated circuits has been the development of efficient CAD (computer-aided design) tools. These tools support the synthesis of complex circuit functions; the simulation of the basic circuits; the design of mask geometries supporting circuit manufacture; the accurate simulation of circuit modules, subsystems, and complete circuits (including layout and process effects); and the testing of finished circuits.

The traditional driving forces in developing new CAD tools have been more complex circuits, improved packing density on the silicon, higher performance circuits, self-testing circuit modules, and better automation of the design process. In terms of silicon efficiency, development has focused on surface area and performance. In general, CAD tools that focus on reducing power have not been developed. New CAD tools are needed so that each parameter in Equation (1) can be considered in the design and implementation of specific circuit functions.

The design process can be divided into the following levels (from highest to most detailed): behavioral, architectural, logic, circuit, and physical (Singh et al., 1994). For low power system design, power minimization methods must be built into the CAD tools at each step. At each design level, the power required must be estimated for a specific application to establish a set of energy conditions as a function of the design alternatives. For low power design, the entire design sequence must be an iterative process, in which the exact power requirement depends on the implementation, which influences higher level design decisions.

Behavioral and Architectural Level Design

At the behavioral level, algorithms and system partitions are selected based on system use. System partitioning can be influenced by the activity level of circuit use and subsystem operating frequency and voltage. Architectural level design consists of mapping and implementing the functional building blocks into hardware building blocks consisting of registers, busses, data paths, and functional blocks representing such things as executing units, controllers, and memories. Often the behavioral and architectural design steps are so closely interrelated (because of the design hierarchy, data flow, and control) that they are combined and optimized together. In this case, system simulation is performed at the functional level to ensure adequate or consistent definition of the functional blocks and interfaces.

At the behavioral and architectural design level, tools will be needed to enable designers to explore, evaluate, compare, and optimize power dissipation alternatives early in the design process. Switching activity and the required operating voltage level for each circuit block can affect the power requirement. Switching activity is a function of the applied data and algorithms and is usually based on extensive simulation using empirical data. At the system level, substantial energy savings can be achieved by identifying common sections of circuitry that can operate at reduced voltage levels. For lower voltage operation, performance compensation can be regained by using special transistors sized for the signal or by implementing concurrency at the architectural level. At the architectural level, energy savings can be obtained by optimizing the instruction set or using a hardware module to implement a specific data path to execute a specific instruction.

Chandrakasan and Brodersen (1995b) present a strategy for voltage scaling in which concurrent architectures are used to retain throughput at reduced supply voltages. In this approach, parallel data paths are used, even though parallel paths and additional wiring increase the total capacitance and the parallel paths operate at slower speed. A similar power reduction can be obtained using parallel memory access with reduced clock rates, as compared to serial access.

Logic Level Design

Logic level design tools process the functional blocks defined at the architectural level, synthesizing the circuit implementation in terms of individual logic gates and switches. The logic level design strategy for power savings optimizes the circuit to obtain low switching activity for nodes that drive large capacitive loads. Power savings can also be obtained during logic synthesis by considering dynamic power dissipation involved with short circuit currents and slew rates, using accurate delay modeling, and matching equivalent signal pins within a specific gate library to minimize capacitive charging loads.

Circuit Level Design

In the final circuit design step, logic gates are implemented at the circuit level, where individual transistors are designed with appropriate interconnections to perform the logic function. Simulation is used to model the detailed operation of the circuit and can be used to predict circuit performance and to calculate or verify the amount of power consumed in each area of the circuit.

Physical Level Design

Physical design usually refers to the design and layout of the individual masks describing each transistor and the interconnections required to implement each circuit module. During mask layout, the goal is to reduce the capacitive load associated with each switching node of the circuit. The capacitance can be minimized by optimally sizing each transistor and interconnect. At the highest level of layout, power minimization must be performed by optimal circuit partitioning and chip floor planning, i.e., geometric placement of the various circuit blocks. At the lowest level, individual transistor gate sizes, transistor placements, and interconnect wire-widths must be tailored to minimize capacitance.

At all levels, circuit performance and total circuit layout area must be included in the power optimization goal and appropriate trade-offs in the design. Special consideration should be given to the layout of the clock circuits because these circuits have the highest frequency and are distributed globally over the chip. The use of multiple clocks, with the switching frequencies optimized for specific functions, and the judicious use of power-down or sleep circuits can reduce energy consumption. At the integrated circuit design level, most physical design tools rely on a library of predefined and simulated cells to implement specific logic functions. These library elements are placed in pseudo-regular patterns and interconnected to implement the functional building blocks. Although many of the cells are manually designed to optimize compact layouts, interactive design tools can be used to simplify layout and analysis for individual logic cells.

Floor planning and circuit partitioning can be used to optimize the layout to reduce power requirements by collecting various circuit and logic functions to minimize off-block capacitance and keep the high switching activity nets within the same block. Individual placement of cells is based on the signal frequency and associated net capacitance. During signal routing, higher priority is placed on reducing the length and capacitance of nets with high switching activity. Depending on the flexibility of the cell library, a power saving can often be realized by tailoring the size of the transistor drivers and the widths of the interconnects for specific nets to reduce total capacitance while maintaining a constant gate delay.

Meeting Unique Army Requirements

All aspects of low power design are addressed in detail at special conferences and in the professional electrical engineering journals, such as journals published by the Institute of Electrical and Electronics Engineers (IEEE) and other publications cited in this chapter. Industry has reduced system power requirements for portable functions dramatically by moving from a simple pursuit of higher performance to a deliberate effort to minimize power. To build and adapt systems to meet its unique requirements, the Army will have to do the same for system, subsystem, and integrated circuit design methods. Contracts with commercial vendors should specify the use of energy-efficient techniques and technologies. If CAD tools that minimize power while minimizing manufacturing costs and maximizing reliability are not available commercially, the Army should support their development for each stage of the design process.

INDUSTRY TRENDS

Semiconductor technology has progressed at a phenomenal rate over the past 30 years. Based on the early development of integrated circuits, Gordon Moore of the Intel Corporation developed what has become known as "Moore's Law": that technology complexity (minimum geometries and circuit density) doubles every 18 months, leading to a fourfold increase in circuit or transistor density every three years.

The semiconductor community has summarized semiconductor technology requirements and developed the 15-year NTRS (National Technology Roadmap for Semiconductors) (SIA, 1994).[1] These requirements, established by extending Moore's Law, involve scaling the minimum feature size by a factor of 0.7 every three years, from one product generation to the next. Table 4-1 shows industry's intent to continue increasing the number of available transistors on an IC while driving the cost per transistor down. Table 4-2 shows the plan for decreasing battery voltage while total IC power continues to increase because of the increasing operating frequency and the number of transistors on the IC. The reference to performance in Table 4-2 reflects the industry's desire to increase the operating frequency and number of circuit functions as transistor sizes decrease, which would lead to an increase in the total circuit power if adequate cooling methods can be used. Although the emphasis is on minimum feature size for the transistor as a function of time, the accompanying decreases in operating voltage and capacitance lead to an overall decrease in the power requirement for a specific circuit function while performance remains constant. More importantly, increased levels integration will support designs for the low power techniques mentioned earlier, such as increasing or repeating circuit functions for lower power

---

[1] The NTRS is revised every three years, and a 1997 revision was in progress at the time of this report.

architectures, adding chip memory to minimize circuit I/O, and selectively powering down circuits.

TABLE 4-1 Semiconductor Product Characteristics

Year of First Shipment	1995	1998	2001	2004	2007	2010
Minimum Feature Size (μm)	0.35	0.25	0.18	0.13	0.10	0.07
Memory						
Bits/chip	0.017	0.007	0.003	0.001	0.005	0.0002
Cost/bit (millicents)	64 Mb	256 Mb	1 Gb	4 Gb	16 Gb	64 Gb
Microprocessor logic (high volume)						
Transistors/cm^2	4M	7M	13M	25M	50M	90M
Memory cache (bits/cm^2)	2M	6M	20M	50M	100M	300M
Cost/transistor (millicents)	1	0.5	0.2	0.1	0.05	0.02
ASIC logic (low volume)						
Transistors/cm^2	2M	4M	7M	12M	25M	40M
Design cost/transistor (millicents)	0.3	0.1	0.05	0.03	0.02	0.01

Source: National Technology Roadmap for Semiconductors, 1994.

The first NTRS was developed in 1992 and revised in 1994. A further revision is expected to be released in late 1997. The road map covers a 15-year time span (six generations of technology development) with minimum feature sizes decreasing according to Moore's Law. Although the road map focuses on the year products are first produced using a new technology, development is generally divided into four distinct phases: research, development, integration, and production. The research phase for a particular technology generation generally precedes production by three technology generations, or eight to ten years.

The road map was created by an official Roadmap Coordinating Group with the support of eight technology working groups representing each critical technology for semiconductor product development and manufacturing: (1) design and test, (2) process integration, devices, and structures, (3) environment, safety, and health, (4) lithography, (5) interconnect, (6) materials and bulk processes, (7) assembly and packaging, and (8) factory integration. Related disciplines, such as metrology, modeling and simulation, electronic materials, standards, contamination-free manufacturing (CFM), and quality and reliability, were included as "cross-cutting technologies."

Although the primary measures of progress have been decreases in minimum feature size and increases in transistor density, smaller feature sizes have led to related changes in fabrication technology, producing circuit operation at lower voltages and decreases in circuit capacitances, which have led to decreases in circuit power. In addition, increasing device densities have made possible dramatic increases in the complexity of circuits on a single chip (leading to "systems on a chip,") with an attendant decrease in power related to driving numerous off-chip capacitances associated with interfacing integrated circuits. Even with the primary emphasis of the NTRS on minimum feature size, the related reductions in power requirements for a fixed level of performance and the increasing levels of device integration would tend to reduce the power requirements of electronics for the dismounted soldier.

TABLE 4-2 Semiconductor Product Technology

Year of First Shipment	1995	1998	2001	2004	2007	2010
Minimum Feature Size (μm)	0.35	0.25	0.18	0.13	0.10	0.07
Power supply voltage (V)						
Nonportable	3.3	2.5	1.8	1.5	1.2	0.9
Portable (battery)	2.5	1.8–2.5	0.9–1.8	0.9	0.9	0.9
Performance						
Microprocessor circuits with cooling (W)	80	100	120	140	160	180
Logic circuits without cooling (W/cm^2)	5	7	10	10	10	10
Maximum power (W)	2.5	2.5	3.0	3.5	4.0	4.5
Design and test						
Test cost/pin ($K)	3.3	1.7	1.3	0.7	0.5	0.4
Number of test vectors (M)	16–32	16–32	16–32	8–16	4–8	4
IC auto test capability (% BIST/DFT[a])	25	40	50	70	90	90+

[a] built-in self-test/design for testability

Source: National Technology Roadmap for Semiconductors, 1994.

Purpose

The NTRS provides a high-quality database of industry goals, related needs to achieve the goals, and a framework that the semiconductor industry and government can use to focus R&D on the desired objectives. Although each critical technology area focuses on different needs, the integrated key elements of the road map are minimum feature size, memory density, logic transistors per cm^2, and cost per bit or function (Table 4-1). Because of the industrial dominance of CMOS technology, CMOS has been used as the standard, and advances in other silicon technologies can be related to CMOS advances. Table 4-3 summarizes overall technology characteristics for an integrated chip and package. The complete road map addresses not only the chip design and fabrication technology, but also materials, including silicon and SOI, and related technology issues, such as power and voltage trends, design and testing tools, and manufacturing defect densities.

Although one objective of the NTRS is to foster and channel creativity in the R&D community, it was also intended to help suppliers anticipate the needs of semiconductor manufacturers. The road map also provides systems designers with a schedule for technology insertion in planning new products. The Army can use NTRS near-term projections to determine the availability of technology for implementing low power circuit designs in defense electronics systems.

Challenges

In addition to describing the industry plan for the availability of technology, the road map summarizes the developments in equipment and manufacturing technology necessary for staying on schedule. Many of these developments are identified as technology gaps that will require additional investment to support the road map. The most urgent "Grand Challenges" facing the semiconductor community in achieving smaller feature sizes and cost reductions (SIA, 1994) are described below.

Improved Productivity

The semiconductor industry has maintained growth by achieving a 30-percent-per-year per function cost reduction throughout its history. The increase in productivity has been achieved through innovations in design, reductions in device size, increases in wafer size, improved yield, and improved utilization of capital equipment. Increases in productivity have been offset by increased chip and technology complexity, chip sizes, and costs of wafer fabrication facilities. The cost of a new fabrication facility now approaches $2 billion. Some historical approaches to higher productivity, such as improving yield, are no longer valid (the yield of most processes is already high). Therefore, new ways must be found to increase productivity if industry is to continue the historical trend in cost (improvements in manufacturing technology are one possibility).

Managing Complexity

Sophisticated tools are required to deal with the exponential increases in the complexity of integrated circuits, including increasing numbers of masks and process steps, more layers of interconnect, special device structures, optical lithography that requires phase-shift masks and proximity correction for a variety of structures, and sophisticated planarization techniques. These new design tools must be able to cope with a factor-of-four increase in complexity with each technology generation, the use of mixed signal designs, and increases in power, stress, and performance. In addition, new portable computing and signal processing requirements imply lower power systems emphasizing design goals other than improved performance.

TABLE 4-3 Semiconductor Package Characteristics

Year of First Shipment	1995	1998	2001	2004	2007	2010
Minimum Feature Size (μm)	0.35	0.25	0.18	0.13	0.10	0.07
Number of I/O connections (IC-to-pkg)	900	1350	2000	2600	3600	4800
IC frequency (MHz)						
Clock speed, high performance	300	450	600	800	1000	1100
IC-to-board speed, high performance	150	200	250	300	375	475
IC size (mm^2)						
Memory	190	280	420	640	960	1400
Microprocessor	250	300	360	430	520	620
ASIC	450	660	750	900	1100	1400
Number of wiring levels (logic)	4–5	5	5–6	6	6–7	7–8

Source: National Technology Roadmap for Semiconductors, 1994.

Advanced Technology

In the past, large industrial organizations have invested heavily in advanced R&D, with or without government sponsorship. These investments have led to technological breakthroughs and leadership in the field by the United States. Although federal support is still available for advanced technology development in industry and universities, government investment has decreased dramatically in recent years.

To ensure that low power technology for the soldier's electronics is available, DARPA should increase support for advanced technology, ranging from research on new electrical devices and circuits to improved manufacturing methods and the development of more efficient software design tools. In particular, large investments are required for facilities and apparatus, especially in the university environment. One challenge will be to distribute research facilities and programs to meet continuing technology requirements. Additional support is required for long-term research in areas such as nano-metrics metrology, nano-fabrication techniques, and new device structures.

Fundamental changes are required in software development to produce high-quality software and in the optimization of cross-disciplinary technology, which requires expertise from a variety of engineering disciplines to provide optimal solutions for specific problems (e.g., expertise in circuits, packaging, processes, software, and mechanical design to solve interconnect problems).

Funding

Although extensive resources are being invested in semiconductor technology, even greater resources are required for research in new technology to develop precompetitive technologies and to eliminate duplication of effort. The entire community, including the government, must support R&D on critical technology components with shared research funds. For example, technologies that are not commercially self-supporting, but are prerequisites for maintaining the technological leadership of the United States, include lithography tools, metrology tools, mask writers, masks, technology computer-aided-design (TCAD) tools, and inspection tools. The challenge is to implement an efficient funding strategy that covers all critical needs and to demonstrate new concepts prior to funding the development of full solutions.

The published road map includes many other details. Because it represents the industry consensus, it is an excellent guide for the DoD regarding the planned availability of advanced technologies. For example, the road map includes plans for circuit complexity, power, and packaging specifications for future systems. In addition to technical plans, the road map provides guidelines for investments in technology and research to support the road map goals, and hence technology availability, for defense applications. One of the key technologies for investment is advanced lithography tools. Smaller devices enabled by advanced lithography will continue to reduce the power required for military integrated circuits.

Military and Commercial Synergy

The Army can take advantage of industry's commitment to staying on the road map by synchronizing its electronics technology cycles with those of industry. By migrating with the technology on a nominal three year cycle, the battery voltage for supporting industry requirements will decrease from 5.0 V in 1996 to 0.9 V in 2004, resulting in a factor of 30 power savings for a specific circuit function, from the voltage decrease alone. Even though the circuit voltage may plateau in the 0.9 V range, continued improvements in transistor density and performance through other technological advances are expected to support lower power integrated circuits.

Although the industry commitment to remaining on the NTRS is strong, extensive resources must still be expended each year to advance the technology. Certain technology developments cannot be adequately funded through commercial sales. Because it could be detrimental to U.S. security for foreign countries to acquire a new technology before the United States and to ensure U.S. technological leadership, the entire community must support R&D on advances in technology. The DoD can help maintain U.S. leadership by supporting the development of critical technology components needed by industry. Supporting technology advances will provide continued leverage for defense electronics, including low power electronics systems for the dismounted soldier.

THEORETICAL LIMITS ON LOW POWER ELECTRONICS

Because the NTRS predicts continued advances according to Moore's Law and does not address theoretical or practical technology limitations, the committee analyzed possible limits on continued advances. Appendix D focuses on the continued reduction in minimum circuit geometries leading to gigascale levels of integration (1 billion transistors per chip) (Meindl, 1995). Although the Army's low power systems may not require the maximum device density or the high performance that accompanies the decrease in design rules or minimum geometries, the lower voltages and capacitances supported by the decreasing device geometries and interconnects and the ability to tailor individual transistor drive currents are expected to yield reductions in both integrated circuit and system power requirements.

Future opportunities for low power electronics or gigascale integration will be governed by a hierarchy of theoretical and practical limits. The five levels of this hierarchy are codified as fundamental, material, device, circuit, and system limits. At each level, there are two kinds of limits, theoretical and practical. Theoretical limits are determined by the laws of physics and by technological invention. Practical limits must, of course, be in compliance with physical limits but must also take into account manufacturing costs and markets. Because theoretical limits define the ultimate capabilities of electronics that could be provided to the dismounted soldier, the most important theoretical limits for low power electronics are discussed here. Broadly speaking, theoretical limits deal with the canonical operation of digital computing, the binary switching transition, and the interconnection of switching elements.

The saturation level of gigascale integration does not approach the physical limits, and it will be possible to continue for at least another decade to reduce feature size and switching energy and increase the numbers of transistors per chip at the exponential rates of the past two decades. Beyond the next decade, however, a viable new suboptical microlithography technology will be required. For example, optical lithography will reach its practical limit at the 0.125 μm generation of chips (or shortly thereafter), and possible alternatives include extreme ultraviolet or soft x-ray lithography. The relatively short wavelengths of these alternatives will require new photon sources, new masking techniques, new resist materials and processes, and new metrologies. The challenges presented by these prospective advances appear to be disproportionately difficult compared to the challenges the semiconductor community has already met. Moreover, the same may be said about virtually all of the associated ultra clean (Ohme, 1994) sub-0.125 μm fabrication processes, such as ion implantation, rapid thermal processing, and plasma enhanced chemical vapor deposition, that must accompany a suboptical lithography technology in a manufacturing environment.

These difficulties can probably be overcome for two reasons. First, the principles of physics are not at all discouraging. Second, the economic incentives for succeeding are virtually irresistible. The prospects of scaling future species of metal-oxide semiconductor field effect transistor (MOSFETs) to 25 nm minimum feature sizes (and perhaps beyond) are promising. Furthermore, between the 25 nm MOSFET and the 0.118 nm tetrahedral radius of a silicon atom are two decades of opportunity to scale dimensions, about as much as has been achieved so far. Discounting any sub-25 nm breakthroughs, between the 125 nm and the 25 nm generations of chips, four or five intermediate generations can be forecast, which should make possible the trillion transistor chip (1 trillion devices), or terascale integration.

Although the potential to scale to 25 nm and beyond exists, the challenge of inventing structures and manufacturing hundreds of billions of sub-50 micron transistors will require enormous research effort by both government and industry. Following the anticipated achievement of the 125 nm generation in about a decade, at a rate of three to six years per succeeding generation, scaling should be expected to continue into the 2020s. Unfortunately, however, engineering challenges associated with the scale reductions forecast by the NTRS and with designing the ultrascale ICs may not be overcome, because DoD has eliminated almost all funding for long-range research on the fabrication and design technologies necessary for continued exponential improvements.

INDUSTRY CONSENSUS

The NTRS outlines the industry consensus about technology directions and advances for silicon. In addition, numerous professional societies, universities, and government agencies have focused on advanced technology development, including the annual IEEE International Symposium on Low Power Electronics and Design and the special IEEE Transactions and Proceedings and the DARPA low power electronics program. Each of these focuses on power reduction for mobile microelectronics.

Centers for Low Power Electronics

Industry's recent focus on low power electronics has spurred academic research. Numerous universities have established low power research programs and, in many instances, special design centers to provide a forum for establishing research directions, discussing industrial needs, presenting early results, and solving specific design problems.

Because of the pervasive need for low power electronics for portable systems, several commercial, professional, and university societies have focused on low power technologies. For example, various academic centers for low power electronics are addressing fundamental, industry-relevant research problems in the design of ultra-low power portable computing and communications systems. These centers are sponsoring basic and applied research for the development of the next generation of mobile and portable ultra-low power electronic systems and are establishing mechanisms for timely technology transfer, including research results and the exchange of scientific personnel among universities and industry. Participating companies advise the academic centers on current and projected industry needs while monitoring and participating in research.

International Symposium on Low Power Electronics and Design

An annual IEEE-sponsored symposium provides a forum for the presentation of advances in low power systems and components. All aspects of designing a low power product, from fabrication technology and circuits to systems and software, are included. The symposium is the result of a merger of separate symposia on low power electronics and low power design and focuses on two topic areas: (1) systems and CAD and (2) circuits and technology. Papers report on significant advances in the field, present new ideas, and often include ways to use new concepts in hardware and practical applications.

DARPA Low Power Electronics Program

The stated goal of DARPA's program was to develop a mainstream technology base to enable a new class of electronic systems that dissipate less than 1 percent of the power of systems based on conventional technology. The program was divided into two sections: circuit architecture and power management; and, materials and device technology. The first area included the development of low power CAD tools, power conversion, recovery, and distribution. The second area started with a conventional 3.3-V bulk CMOS technology with migration to a 1.0-V SOI CMOS process. In both areas, the emphasis was on verification and integration with demonstration of a viable SOI design and manufacturing process in a low power, high-performance electronic system. Although many industry achievements are proprietary, the program demonstrated a capability of 0.9-V operation with power requirements of 0.01 mW/gate-MHz.

The DARPA program successfully demonstrated significant reductions in power for a variety of applications and has provided enabling research funding to universities for low power research. Because of the importance of low power research to the Army, a follow-on program should be initiated.

FINDINGS

Continued progress in silicon technology over time has led to dramatic decreases in device sizes, improvements in circuit performance, increases in the density and complexity of circuits on a single integrated circuit, and decreases in energy requirements per circuit function. The NTRS outlines industry's technology development plan. In response to market demands, the commercial sector continues to produce products with expanded capabilities to meet consumer demands. These advances can be leveraged if the Army can synchronize its upgrades with commercial advances. Keeping pace with industry would support the military policy of using more commercial-like products to control costs. With major technological advances being made approximately every three years in industry, substantial decreases in power are possible for specified functions, which can mean a longer mission time for a fixed energy source, a decrease in weight and volume if the source is scaled for the same mission time, or an increase in functionality for a fixed mission and source. In any case, significant advantages can be realized.

Keeping pace with industry and upgrading technology every three years may require restructuring the Army's design and procurement process so that contractors automatically upgrade designs as improved technology becomes available. For example, a basic ASIC (application-specific integrated circuit) design could be implemented using a high level design language specification and the designs simply recompiled periodically with the latest technology. This concept could be enhanced by using modular designs. A policy could require limiting procurement for a specific technology lot and could require discarding older products. A "throw away technology" approach would be similar to the present commercial practice of upgrading personal computers every few years. By correlating military procurements with commercial specifications, the Army could realize many of the volume cost advantages, as well as technology advantages, enjoyed by commercial consumers.

To keep up with industry trends in reducing power for mobile functions, Army contractors will need to change their system, subsystem, and integrated circuit design methods. Instead of designing for the smallest chip area or the highest speed, they should design for minimum power requirements. This new approach would require the development of CAD tools (system architecture, circuit design, and layout) that minimize power and manufacturing costs and maximize reliability—design tools that are not available commercially.

The NTRS defines critical technology areas and in some cases identifies research gaps that may prevent technology breakthroughs. Because the road map is upgraded regularly (every three years), the Army can provide input through DoD representation on the road map committee or through other government representatives, such as the National Institute of Standards and Technology or the national laboratories. The Army can use the road map to project the availability of technology in specifying new systems. Supplemental R&D support will be necessary for industry and universities in specific areas to maintain the road map schedule. Because much advanced technology development in the past has been done at universities, the Army should continue to encourage funding from DoD to universities through the Army Research Office and DARPA.

A number of special conferences, symposia, and focus centers have been created to encourage interest and advancements in technologies for low power electronics. Although Army and contractor personnel normally participate in many conferences, the Army could alert industry and university researchers to specific defense needs by formally joining several university focus centers and supporting projects that are aligned with Army needs. Participation in the specialty center activities and conferences is one way for the Army to obtain up-to-date information, to inform the centers and industry about military needs, and to provide the Army with information on available technologies, architectures, and designs.

Software development should also focus on minimizing power requirements. Each instruction should be written or compiled to minimize power. Software implementation is related to logic design and physical circuit design. Although private industry may have software development tools that minimize power requirements, the Army may have to develop new tools to compile application software to minimize power for military applications.

The general trend in mission planning has been to provide general-purpose capabilities for each soldier. The aim has been to maintain as much latitude as possible to support new mission requirements and also to capture cost savings by procuring standardized, interchangeable systems. Providing standard, general capabilities, however, requires a good deal of overhead that increases power requirements. The electronics systems that require low power performance should be tailored to meet specific soldier needs. Power overhead functions can be minimized by using dedicated circuit and subsystem hardware instead of general-purpose programmed hardware and circuits. Although general-purpose electronic circuits support product standardization and maximize the number of applications, they usually consume more system power than necessary. By designing custom circuits for dedicated functions, the total system power can be reduced.

5

Communications, Computers, Displays, and Sensors

The communications, computers, displays, and sensor systems for the dismounted soldier will provide the soldier with information about location and surroundings, evaluate tactical intelligence, assist in targeting, and permit voice and data communications with squad members and field operations centers. These systems will be introduced with modest capabilities in the fully developed Land Warrior equipment and will evolve to higher performance levels to meet increasing demands. Unfortunately, the Land Warrior systems will require a large amount of electric power. Table 5-1 lists estimated power requirements for the communications, computing, display, and sensor functions of the Land Warrior system.

The data in Table 5-1 clearly indicate that most of the energy dissipated in the Land Warrior system will be associated with the radios and computers to be carried by soldiers and, therefore, that the electronics associated with communications and computing functions afford the greatest opportunities for energy savings. The challenge for future Land Warrior systems and successor systems will be to reduce electrical energy consumption while increasing performance to meet projected increases in communications bandwidth, data file sizes, and computational performance.

It is important for the Army to recognize that the electronics industry faces similar challenges in commercial markets and is developing a wide range of low power technologies and design methodologies that are directly applicable to portable military equipment. These emerging technologies will have such a dramatic impact on the energy consumed in performing digital electronic functions—reductions anywhere from a factor of 10 to a factor of 50 are possible—that the Army must either use them or risk fielding equipment that is markedly inferior to commercially available equipment.

Specifically, industry is being driven to increase the performance and simultaneously improve the battery life of commercial products, including portable communications equipment, such as cellular phones and pagers; portable computing devices, such as laptops, palm-tops, and pocket organizers; and portable audio and video equipment, such as camcorders, audio tape and CD players, and portable television sets. Low power technologies and design methodologies are being developed in the following general categories:

TABLE 5-1 Power Requirements of the Land Warrior System by Function

Function	Operating Power
Communications	
Soldier radio	7.4 W
Squad radio	14.0 W
Computer	14.8 W
Displays	
Hand-held flat panel display	6.4 W
Helmet-mounted display	4.9 W
Integrated sight module display	2.6 W
Sensors	7.9 W

- low-voltage semiconductor processing technology
- power optimizing hardware design methodologies
- power optimizing software design methodologies

This chapter reviews commercial trends that are driving the development of low power technology. It describes how new low power technologies and design methodologies are being used to design commercial products, details the magnitude of improvements in performance, and projects improvements that may be possible in the future. Subsequent sections contain detailed studies of the communications, computing, sensors, and display equipment to be used by Land Warrior, along with descriptions and assessments of enabling technologies.

TRENDS IN DESIGNING COMMERCIAL PORTABLE EQUIPMENT

Suppliers of portable consumer electronics face conflicting demands of increasing performance while decreasing power drain[1] in order to provide longer battery life. Two of the best examples are cellular telephones and laptop computers. Figure 5-1 plots the complexity of high performance microprocessors by the year each device was introduced. The graph shows that microcomputer complexity has increased by a factor of ten every seven years, following Moore's

---

[1] Power is a rate of change, so the term "power drain" is technically imprecise. The term is never the less widely used in industry to describe the power performance of microprocessing devices as measured in mW per MIPS.

Law of integrated circuit complexity (see Chapter 4). Figure 5-2 plots the complexity of radio pagers and cellular phones by year of introduction. Predictably, it shows that the complexity of these products is driven by the complexity of integrated circuits; these slopes also follow Moore's Law. A frequently unrecognized implication of the data in Figures 5-1 and 5-2 is that, because power drain tends to track complexity, the power requirements of semiconductor products have also increased exponentially. The thousand fold increase in complexity over the past 25 years has driven circuit complexity to the point that power drain has become a major problem facing the electronics industry.

The power dissipation of a digital logic integrated circuit is determined by several factors, including the operating voltage of the circuit, the complexity of

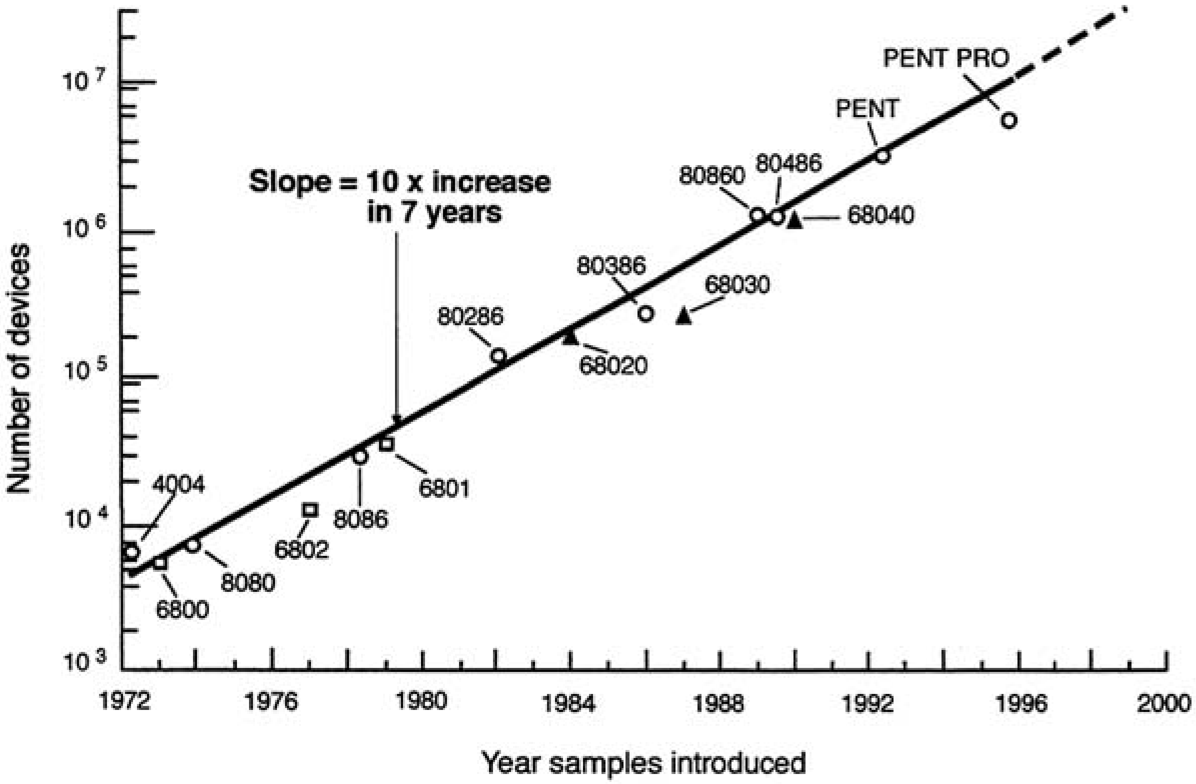
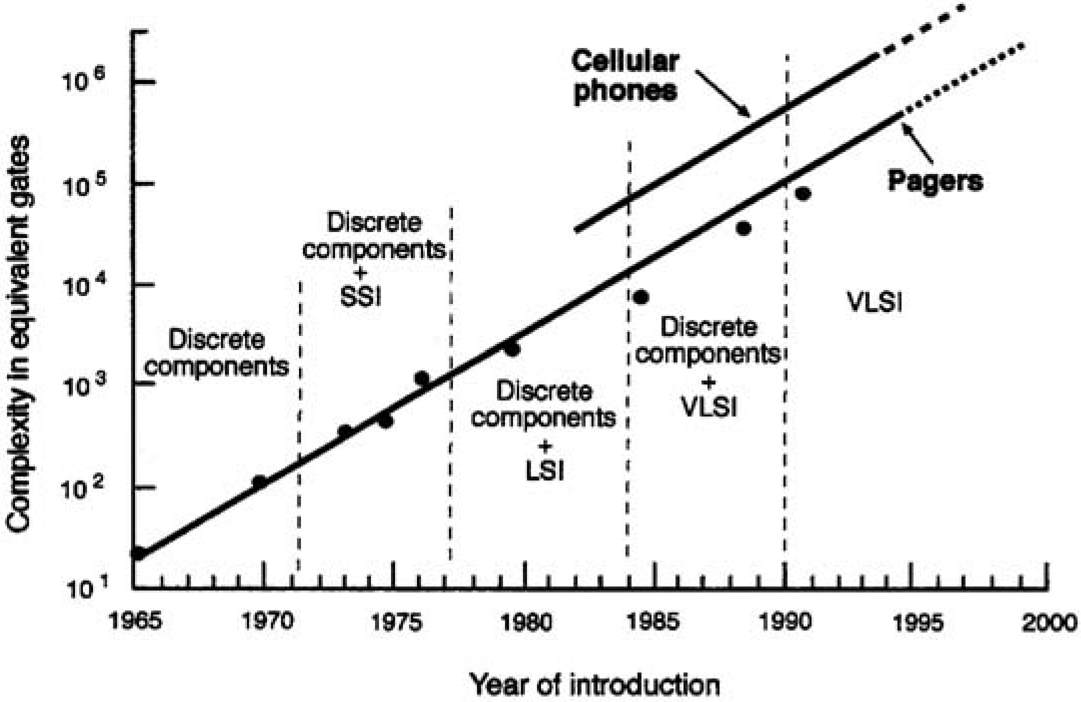


FIGURE 5-1 Complexity of microprocessors by year of introduction.



Notes
SSI = small scale integration
LSI = large scale integration
VLSI = very large scale integration

FIGURE 5-2 Complexity of cellular phones and pagers by year of introduction.

the circuit, the operating frequency of the elements of the circuit, and the speed-power product of the process used to fabricate the circuit. For a circuit in which all of the logic elements operate at the same frequency, the relation of these parameters can be expressed as:

$P_d \sim K_p \cdot C \cdot F \cdot SP$ (1)

P_d = power dissipation of the circuit. K_p = a process and supply voltage dependent constant. C = the complexity of the circuit in equivalent gates. F = the operating frequency of the circuit. SP = the speed-power product of the semiconductor process.

Thus, two major factors besides complexity influence power drain: the operating frequency of the logic and the speed-power characteristics of the semiconductor process.

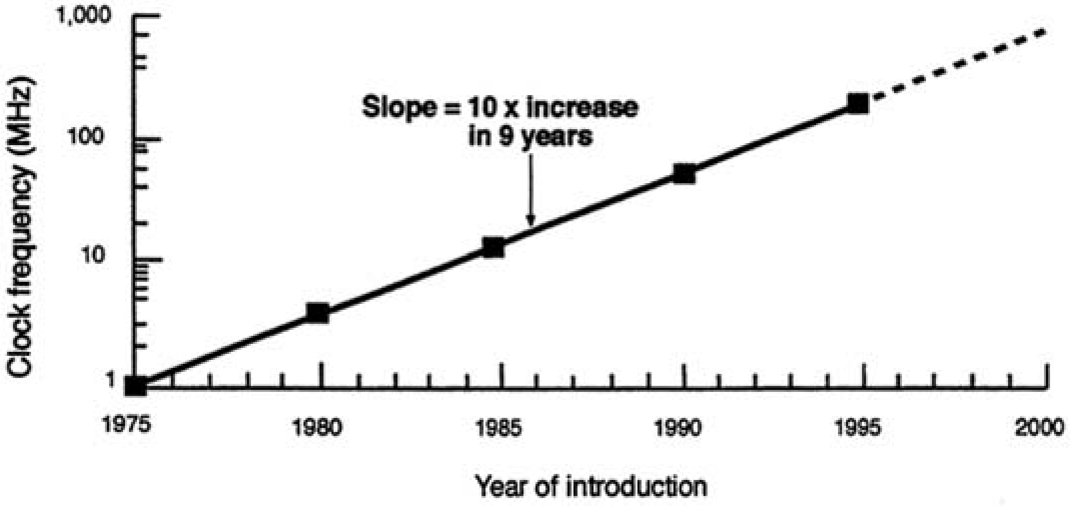


FIGURE 5-3 Operating frequency of high-end microprocessors used in desk-top computers by year of introduction.

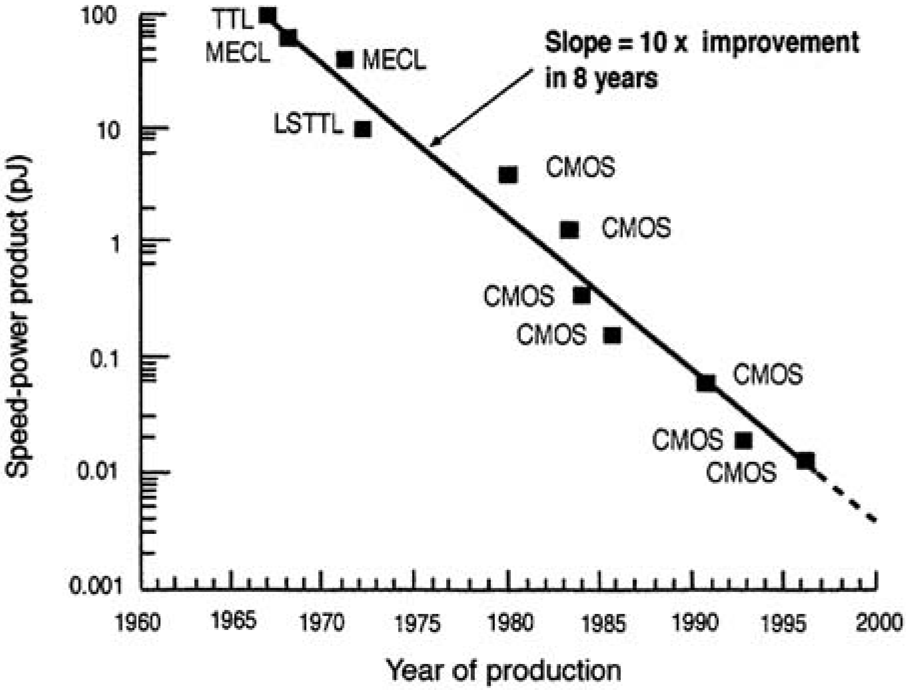
Figure 5-3 plots the operating frequency of the high-end microprocessors used in desktop computers. Performance, measured by maximum operating frequency, has increased steadily, by a factor of ten every nine years. The performance of other digital logic functions, such as digital signal processors and numeric coprocessors, has followed a similar trend.

This performance trend is well known and has been one of the main reasons for the success of the personal computer and workstation industries, as well as most consumer electronics products. The frequently unrecognized implication of this trend has been an exponential increase in the inherent energy consumption of very-large-scale integrated (VLSI) circuits. Taken together, the data in Figures 5-1 and 5-3 indicate that two of the factors in Equation (1), complexity (C) and frequency (F), have been increasing at a combined exponential rate of a factor of 100 every eight years.

Figure 5-4 plots the speed-power efficiency of several bipolar and CMOS (complementary metal-oxide semiconductor) integrated circuit processes by the year they were first used for commercial production. Speed-power efficiency has improved by a factor of ten every eight years. Although this improvement closely tracks the increase in complexity of VLSI chips, it does not compensate for the combined rate of increase in complexity and performance. Indeed, the net combined rate of change in the three parameters in Equation (1) is a tenfold increase every eight years.

The semiconductor industry has been rapidly approaching a situation in which power will become a major barrier to further improvements in complexity and performance. The problems include: poor battery life for portable equipment;

heat dissipation and cooling problems for high-performance chips and systems; and reliability problems associated with elevated operating temperatures of semiconductors.



Notes

TTL = bipolar transistor-transistor logic
MECL = bipolar emitter coupled logic
LSTTL = low power Schottky TTL
CMOS = complimentary metal oxide semiconductor

FIGURE 5-4 Improvement in the speed-power characteristic of integrated circuit processes by year of introduction.

Until recently, the electronics industry has not paid much attention to power drain and its associated problems. This situation is highlighted in Figure 5-5, which shows the power drain per million instructions per second (MIPS) of the leading commercial microprocessors through the year 1993. The chart shows that there was essentially no reduction in the power drain of these products through 1993. The power efficiency on a mW/MIPS basis actually degraded over time. In fact, the first samples of the Pentium™ processor reportedly overheated because they exceeded the dissipation limit of their packages!

The products shown in Figure 5-5 are high-end microprocessors designed for desk-top applications, for which power drain was not considered an important design parameter. The only power consideration was that the devices should not exceed the heat dissipation of the planned packaging. In the early 1990s, however, cellular telephones, personal digital assistants, laptop computers, camcorders, and other portable products began to sell in significant numbers. Battery life became an important design issue for these products, and new microprocessor designs aimed at optimizing performance per unit of power drain appeared on the market.

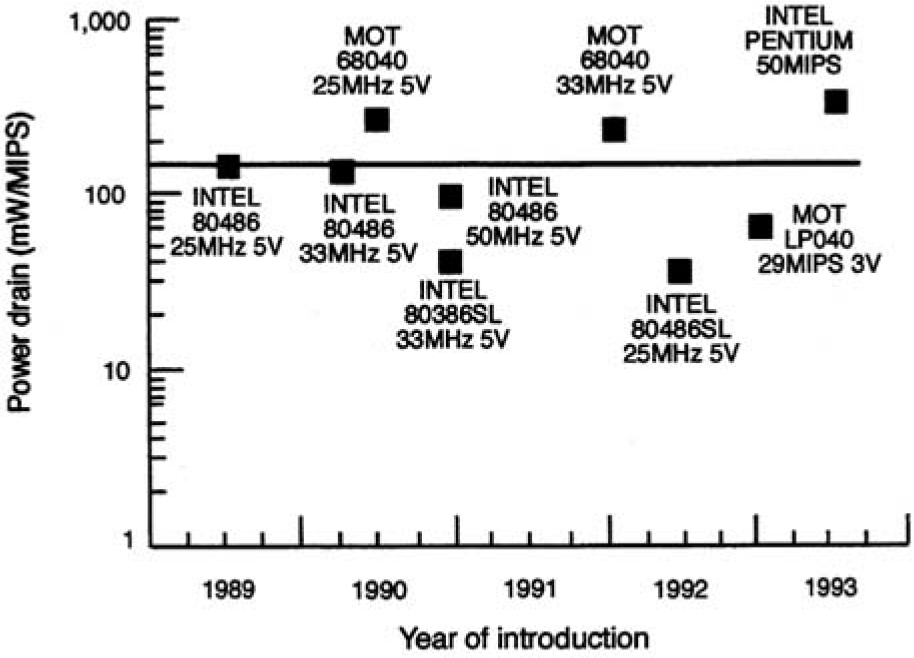


FIGURE 5-5 Power drain versus performance for microprocessors used in desk top computers from 1989 to 1993.

The improvement in the performance of several products is shown in Figure 5-6. Here, products such as the ARM™ central processor unit (CPU) from Advanced RISC (reduced instruction set computer) Machines and the Hobbit™ from AT&T, showed significantly better performance per unit of power (by a factor of 25 in the case of the ARM processor). Subsequent products from NEC and Hitachi, together with process improvements and design changes that allowed low-voltage operation, have pushed the power per MIPS figure down to 1 mW. One of the most startling aspects of the data in Figure 5-6 is that the power required by microprocessors designed for portable, battery-operated devices is decreasing at the astounding rate of a factor of ten in two-and-one-half years. To show that this is not an isolated case, Figure 5-7 plots the same performance for communications-oriented DSPs and shows that they are being improved at the same rate.

The recent improvements in microprocessors and general-purpose programmable DSPs are being driven by a number of design and implementation changes:

- First and foremost, power drain is being treated as a key design parameter.
- Architectures are being optimized for each application. In the case of microprocessors, small, power efficient RISC CPUs are being developed and used for portable applications over the larger complete instruction set computer (CISC) architectures, such as the Pentium™, that are used in desk-top computers. For example, the ARM™ RISC CPU contains 35,000 transistors, compared with 187,000 in the PowerPC™.

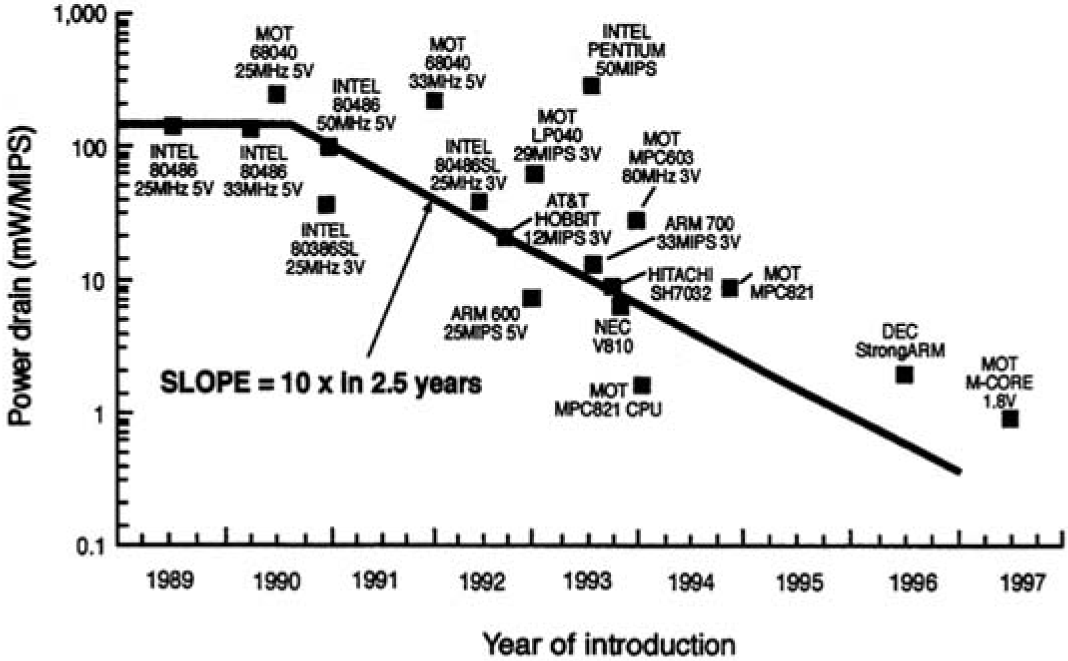


FIGURE 5-6 Power drain characteristics of recent microprocessors.

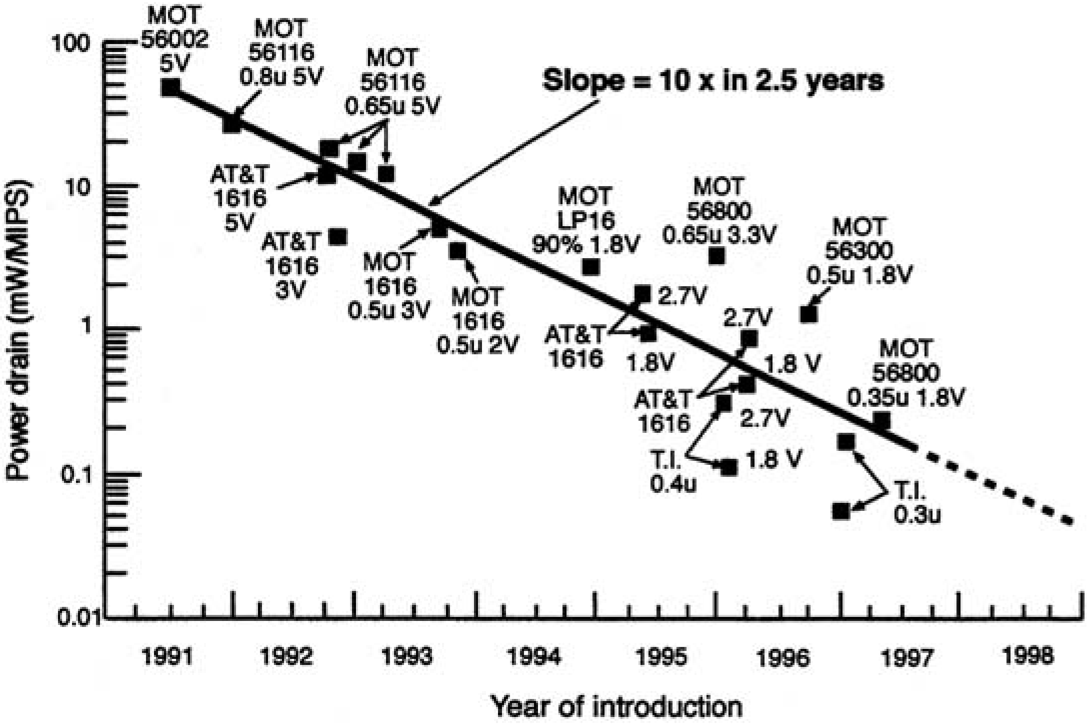
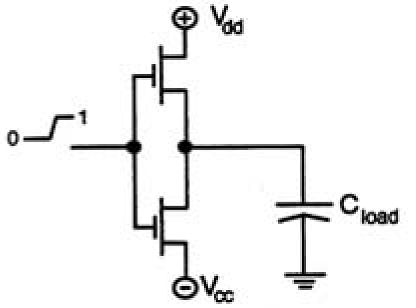


FIGURE 5-7 Performance of general-purpose programmable DSP by year of introduction.

- Low power design techniques are being developed and used with the same priority previously given to maximizing speed and other performance parameters. Examples of these techniques include removing clock signals from unused functions, selecting devices that are sized to optimize speed and power, and selecting the lowest function operating speeds necessary to complete tasks.
- Operating voltage is being lowered to the lowest practical value.

Of all the system parameters affecting power drain, changes in operating voltage have the greatest impact. As illustrated in Figure 5-8, the power drain of the basic complementary logic gate structure is proportional to the square of the system operating voltage. This relationship yields the normalized power drain versus operating voltage slope shown in Figure 5-9, which indicates that a 30-fold reduction in logic power could ideally be achieved by lowering the supply voltage from 5.0 V to 0.9 V.

In practice, it is difficult to implement high-performance logic functions that operate at 1 V today, but substantial power drain reductions have been achieved by moving from 5.0 V to 3.3 V for portable computer systems and cellular phones (a factor of 2.3) and to 2.0 V for consumer audio products (a factor of 6.25). These voltage changes have been achieved by using fairly straightforward modifications of the basic CMOS fabrication processes used in the early 1990s. However, industry is working toward advanced low-voltage



Power drain = load power
+ crossover power loss

$$\text{Power drain} = K_1 fCV^2 + K_2 fV^2$$

$$\text{Power drain} = K\,fV^2$$

FIGURE 5-8 Basic complementary gate structure.

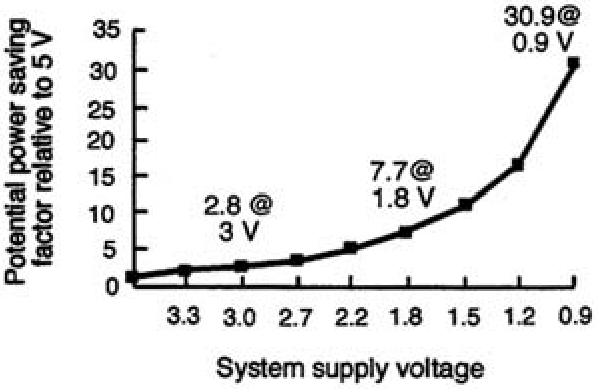


FIGURE 5-9 Power savings of low-voltage logic operation.

semiconductor processes that can implement high-speed logic at even lower voltages, and microprocessors and DSPs that provide more than 250 MIPS at 1.5 V should be commercially available by the year 2000.

Manufacturers of portable equipment, at the product level, are using many of the techniques used by component-level designers, as well as several system-oriented methodologies that significantly reduce power drain. These techniques include:

- System supply voltages are being lowered, and the operating voltage of major subsystems is being selected to optimize both the energy efficiency and the performance of the element. DC-DC converters (Chandrakasan et al., 1994) are often used to provide different supply voltages for key subsystems as shown in Figure 5-10. In camcorders and cellular phones, for example, a "high" voltage battery (typically 6 V) directly supplies analog functions, such as RF power amplifiers or auto-focusing motors that operate best at 5 V, while high-efficiency DC-DC converters are used to supply 2 or 3 V to digital elements. The overall effect is a significant reduction in power drain compared with schemes that operate all functions at the same supply voltage or use loss regulators to generate the lower voltages.
- System architectures are being developed to lower power drain. Examples of this approach include: function-level designs that use parallel logic elements to reduce the operating frequency of each element and the total power drain of the function while maintaining overall performance; and, system and function designs based on new algorithms that reduce power drain.
- The implications of implementing functions in hardware versus software are being studied carefully, and many functions that have been software-based are being implemented in hardware to reduce power drain. One example of this is the 50-fold reduction in power achieved when the trellis decoding function used in cellular telephones was switched from software to hardware.

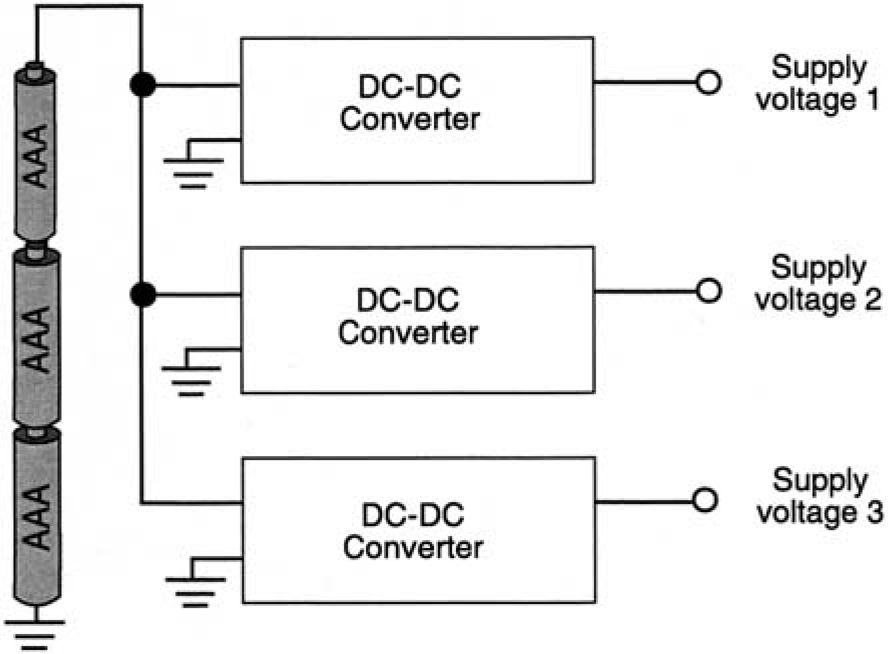


FIGURE 5-10 Power distribution used in portable products.

- Commercial portable product designs are quickly adopting ASIC (application-specific integrated circuit) and system-on-a-chip design methodologies (explained in Chapter 4). These methodologies make many of the techniques described above practical by providing the means for implementing them. The reduction of supply voltages is facilitated, for example, because in the ASIC environment elements can be designed to operate at optimal voltages; the same low-voltage performance may not be duplicated using commercial components.

The single chip environment readily accommodates the implementation of architectural level changes with the greatest potential impact on power drain. The single chip environment eliminates the large interconnect capacitances associated with multichip systems. In high speed systems, driving signals across interchip connection paths requires significant power; in many computer systems this accounts for most of the system power. This point is highlighted in Figure 5-11, which plots the power drain associated with single-line and eight-bit bus interconnects as a function of frequency for line capacitances of 10 picofarads (pF) and 100 pF. The 10 pF load is typical of single-chip systems; the 100 pF load is typical of printed circuit board systems. The data show that, at high frequencies, power lost in the system interconnect can actually exceed power drain in the computer core. This has motivated commercial equipment designers to use highly integrated system chips to minimize losses associated with multichip system implementations. The Army will have to follow suit to reduce losses associated with printed circuit board interconnects in its high frequency systems.

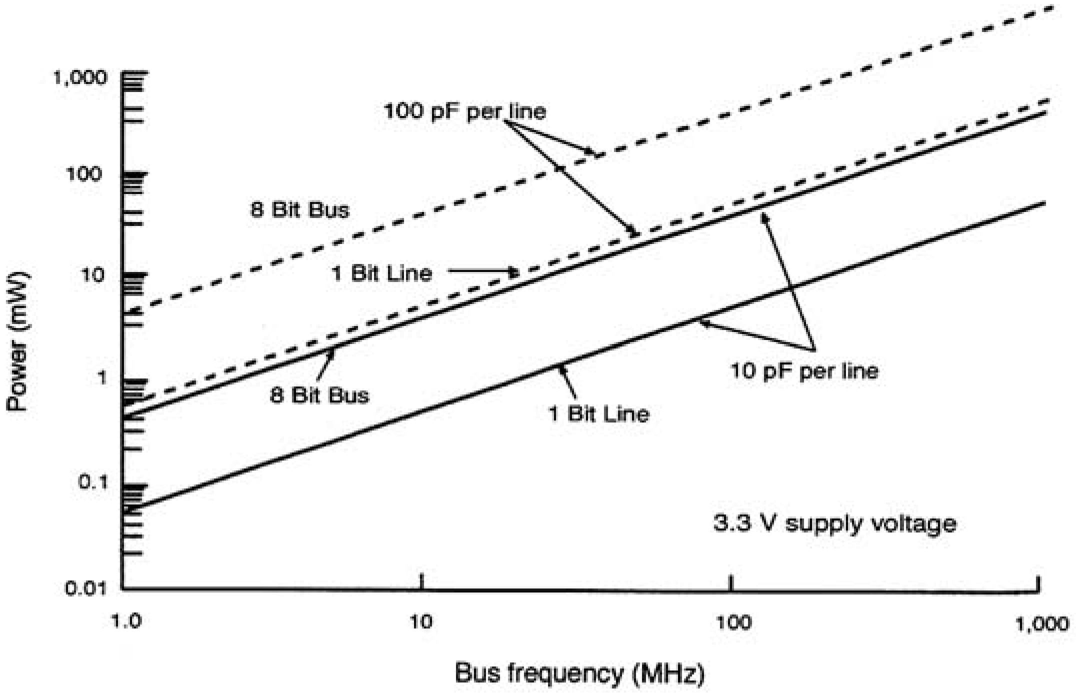


FIGURE 5-11 Power dissipation due to system interconnections.

Taken together, the net effect of the design and methodology changes discussed in this section has been to reduce substantially the power drain of key component-level functions, such as microprocessors and DSPs, and of system-level products, such as cellular telephones, camcorders, and portable computing devices. At the component level, the power drains of microprocessors and DSPs have been reduced by a factor of 100 over the past five years, and further improvements of at least a factor of five are anticipated as new low voltage semiconductor processes move into production. At the product level, improvements of a factor of ten have been achieved, and further improvements of at least a factor of ten are anticipated as the new low power components and processes are introduced commercially.

Examples of product improvements made possible by these advances abound. Talk time of cellular phones has improved from 20 minutes for very large "brick" phones to more than 150 minutes for pocket-size phones. Battery life of popular Walkman™ portable devices has improved from two hours when they were first introduced to more than 20 hours with recent designs. The Army will have to find a way to apply these technology improvements to the design of future equipment. Otherwise, a future enemy may be able to buy more energy-efficient equipment with better capabilities in a local electronics store.

The remaining sections of this chapter review power performance and energy characteristics of the Land Warrior systems communications, computers, displays, and sensors as they relate to the best commercial technologies. Like the electronics in commercial products, the electronics associated with Land Warrior systems have great potential for energy savings.

COMMUNICATIONS

The radio communications-electronics to be used by the dismounted soldier as part of the Land Warrior system consist of a soldier ratio that will be carried by every soldier in the squad and a separate squad ratio carried by the squad leader. The soldier radio will be used for intrasquad communication and is designed to have a communications radius of 1 km. The squad radio will be used for intersquad and squad-to-headquarters communications, with transmission ranges of from 1 to 5 km. Both radios will be linked to the Land Warrior computer.

The two radios will be compatible with each other to the extent that the squad radio must be able to route intersquad voice and data traffic from soldier radios to higher command levels. In part, this will be accomplished using existing combat net radios, but the vision of the digitized battlefield is to link the hierarchy of soldier and squad radios to high-speed, wide-bandwidth communications channels connected with higher levels of the command hierarchy. The resulting network would be able to collect and distribute tactical information and thereby increase situational awareness at all levels.

Power Objectives

The soldier radio will be a small, lightweight, low power voice and data radio that uses standard Army signaling protocol. It will be used to provide voice and data communications among members of the squad. Although the design is not final, power goals for the soldier radio in the Land Warrior system are to provide reliable voice and data communications using 1.4 W in the standby, or listen, mode and 6.0 W in the transmit mode.

The squad radio will be a voice and data radio compatible with the single channel ground airborne system (SINCGARS) combat net radios already in Army service. To ensure compatibility with SINCGARS, it will be necessary for the squad radio to include the following features:

- frequency modulation (FM) operation in the very high frequency (VHF) band from 30.000 to 87.975 MHz
- single channel and frequency hopping modes of operation
- 25 kHz channel spacing for 2,320 operating frequencies
- support for analog voice and data communications
- digital data communications rates up to 16 kbps
- support for encrypted secure communications

It is well known in the Army that the SINCGARS radio is unable to support the high data rates needed for the digitized battlefield. The peak SINCGARS data rate is only 16 kbps, but megabits per second of channel capacity are needed to transport real-time images, video, and other tactical data. For this reason alone, the squad radio will have to be much more than a scaled-down version of the SINCGARS man pack radio set.

Transmitter Energy Consumption

Transmitters account for most of the energy consumed by radios. For a radio to be energy-efficient, practically all of the energy consumption should occur in the final amplifier stage, and the antenna should be matched to the output to minimize energy losses at the antenna interface. In both soldier and squad radios, the transmitting power must be consistent with operation at high data rates. Figure 5-12 plots on a logarithmic sale the radiated power for a hand-held transmitter to communicate reliably at 75 MHz as a function of distance and data rate for a particular set of operating conditions. The data shows that, even though a radiated RF (radio frequency) power of 0.6 W will operate at 16 kbps at 1.5 km, the power must be raised to 6 W to communicate at 160 kbps, and to 60 W at 1.6 Mbps. Clearly, any data rate above a few hundred kbps is incompatible with the reduced size and weight goals of the Land Warrior radios.

The data on radio propagation path losses presented in this section indicate that significant power and energy are required to communicate over the required distances for the soldier and squad radios. These power and energy levels are set by the path losses associated with propagation across difficult terrain in adverse weather conditions and cannot be reduced without fundamentally altering the basic architecture of the radio communication network used in the battlefield. The significance of the network architecture for providing reliable transmission as well as for meeting energy goals is discussed in detail in Chapter 6.

Subsequent sections of this chapter will show that the energy consumption of the other functional elements of the Land Warrior system can be reduced significantly; but radio systems are destined, by basic laws of physics, to use the most power.

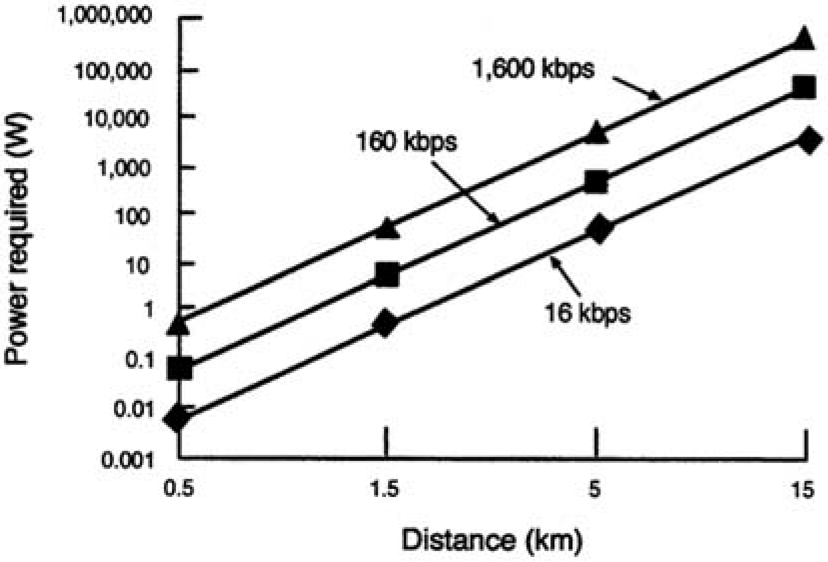


FIGURE 5-12 Radio frequency power required for reliable communications.

COMPUTERS

The current design for the Land Warrior computer is based on commercial personal computer (PC) technology. Like the Army, commercial PC manufacturers have focused primarily on performance and been less concerned with reducing energy consumption. Only modest improvements in the power requirements of commercial PC-based systems have been made. Power drain has been reduced in some PC-based systems similar to the Land Warrior computer, however, and additional energy savings can be achieved without sacrificing performance.

Land Warrior Computer

The Land Warrior computer prototype is based on a commercial 50 MHz 486 processor and uses a variety of plug-in modules to add functions to the basic unit. These modules, linked via industry-standard PCMCIA (personal computer memory card international association) interfaces, include the global positioning system (GPS) receiver and the soldier (intrasquad) radio. The software runs on a standard general-purpose operating system defined by the defense information infrastructure common operating environment (DIICOE), and both the software and the operating system are stored on a hard disk.

TABLE 5-2 Power Requirements of the Land Warrior Computer

Function	Cumulative Peak Power (W)	Function Operating Power (W)	Standby (Alert) Power (W)	Operating Duty Cycle (%)	Average Operating Power (W)
Processor card	4.3	3.6	0.5	90	3.88
Hard disk	3.0	1.9	0.6	10	1.02
Flash memory	1.1	0.9	0.0	1	0.01
RS232 #1	0.8	0.7	0.00	40	0.33
RS232 #2	0.8	0.7	0.00	10	0.08
Tactical communications interface module (TCIM)	1.1	0.9	0.0	20	0.21
Video processor	2.0	1.7	0.0	15	0.30
Audio ampere/ processor	3.0	2.5	0.20	40	1.33
Information security	1.2	1.0	0.18	10	0.33
Power management	0.5	0.4	0.00	100	0.48
Motherboard	0.2	0.2	0.0	15	0.24
Keyboard	0.1	0.1	0.0	5	0.01
Remote input pointing/positioning device (RIPD)	0.1	0.05	0.0	90	0.05
Synchronous serial I/O	0.2	0.15	0.0	0	0.00
TOTAL	18.4	14.8	1.48	—	8.27

Table 5-2 lists the estimated power requirement for the major computer subsystems. The data reflect a 90 percent duty cycle factor for the computer because the Land Warrior architecture uses the computer as a central processing hub for other elements of the system, including the radio—a configuration that precludes the use of conventional power management techniques because the computer must continually monitor the radio for incoming messages.

Because the soldier computer must meet the standardization requirements of the DIICOE, each soldier is technically obligated to carry 100 megabytes of operating system and application software. This use of a general-purpose operating system increases system complexity because more random access memory (RAM) and program memory and a higher system clock rate are needed to store and execute the operating systems and applications, thereby increasing energy consumption. The hard disk drive used to store operating system and programming files itself consumes considerable energy.

In addition to increased energy consumption, using complex software generates logistical problems associated with managing software updates and installing software. General-purpose operating systems are also prone to crashing and leaving other systems dependent on the computer inoperable until the computer is rebooted.

General-Purpose Computing Trends

Computer systems are typically compared using two classes of metrics: capacity and performance. Capacity is how large a component is or how much information it can store. Performance is measured in functions per unit time (often referred to as bandwidth or throughput) or, conversely, the time needed to complete a specific function (referred to as latency). Recently, ease of use has become a major differentiator between computer systems and, hence, represents a third class of metrics.

Metrics for measuring hardware capacity and performance directly reflect the state of technology and are associated with the attributes of common elements of a computer system. Six metrics are commonly used to measure computer performance—processor speed, the size of the RAM, the capacity of the disk memory, the size of the display, the bandwidth of the network communications link, and the distance the computer can roam from a network access point. Two other metrics, energy consumption and physical size, are also becoming important as computers become more mobile.

Table 5-3 summarizes the current range of values for these eight metrics for three classes of computer systems: high-performance workstations, laptop computers, and personal digital assistants (PDAs), also known as palm-top computers. In the table, processor performance is measured in MIPS (millions of instructions executed per second); capacity-related parameters are measured in information units, such as bytes or pixels; communications throughput is measured in bits per second; energy consumption is measured as the reciprocal of the power in kilowatts; and the physical size is presented as the reciprocal of the product of the weight times the volume of space occupied. Note that for all of these metrics, larger numbers are associated with higher performance.

The three columns in Table 5-3 include a contemporary workstation (an anchored, unmovable system), a contemporary laptop computer (a luggable system), and a palm-top computer (a portable, pocketable system). Siewiorek, Bell, and Newell (1982) considered the concept of computer class in attempting to integrate many details of computer systems into an overall evaluation, grouping similarly evaluated systems together. They observed that computer classes differ in physical dimensions and price by roughly 1.5 orders of magnitude (approximately a factor of 30). As each computer class evolves, new members of the class are expected to have increased capacity and functionality. Improvements in technology increase the capacity and functionality of a class. Thus the boundaries of various attributes can be considered to be increasing with time as depicted in Figure 5-13, where each metric is plotted on a logarithmic scale.

TABLE 5-3 Capacity and Performance of Computer Systems

Components	Units	Workstation	Laptop	Palm-top/PDA
Processor	MIPS	400	150	15
Random access memory (RAM)	millions of bytes	128	16	4
Disk memory	millions of bytes	4,000	400	—
Display	millions of pixels	1	0.307	0.115
Network communications	millions of bits/second	100	10	0.0338
Distance	meters	—	100	10,000
Energy consumption	1/kW	5	125	1,000
Physical size (1/weight x volume)	1/kg x m^3	3	200	6,000

Technological advances have created three successive computer classes with each succeeding class exhibiting functionalities identical to its predecessor. The three classes of computers have followed practically the same evolutionary path as capacity and functionality have increased. The newer computer classes have benefited from the evolutionary process of older classes, adapting to proven concepts quickly whereas the older classes required a trial and error process. Siewiorek, Bell, and Newell (1982) observed that computer classes tend to lag behind each other by approximately five years. Thus the palm-top computer of today could be considered to have approximately the functionality of a laptop of five years ago or a workstation of ten years ago. There is little doubt that the palm-top will have the attributes of today's high-performance workstation by the year 2007.

Customized and General-Purpose Architectures

A new class of "wearable computers" is emerging. Wearable computers weigh only a few ounces, operate for months or years on a single battery, and have esthetically pleasing shapes that can adorn various parts of the body. Pagers and electronic watches (incorporating calculator and memory storage functions) are the first examples of the wearable class of computers. This new class can be expected to have at least the functionality of today's laptops by the year 2007.

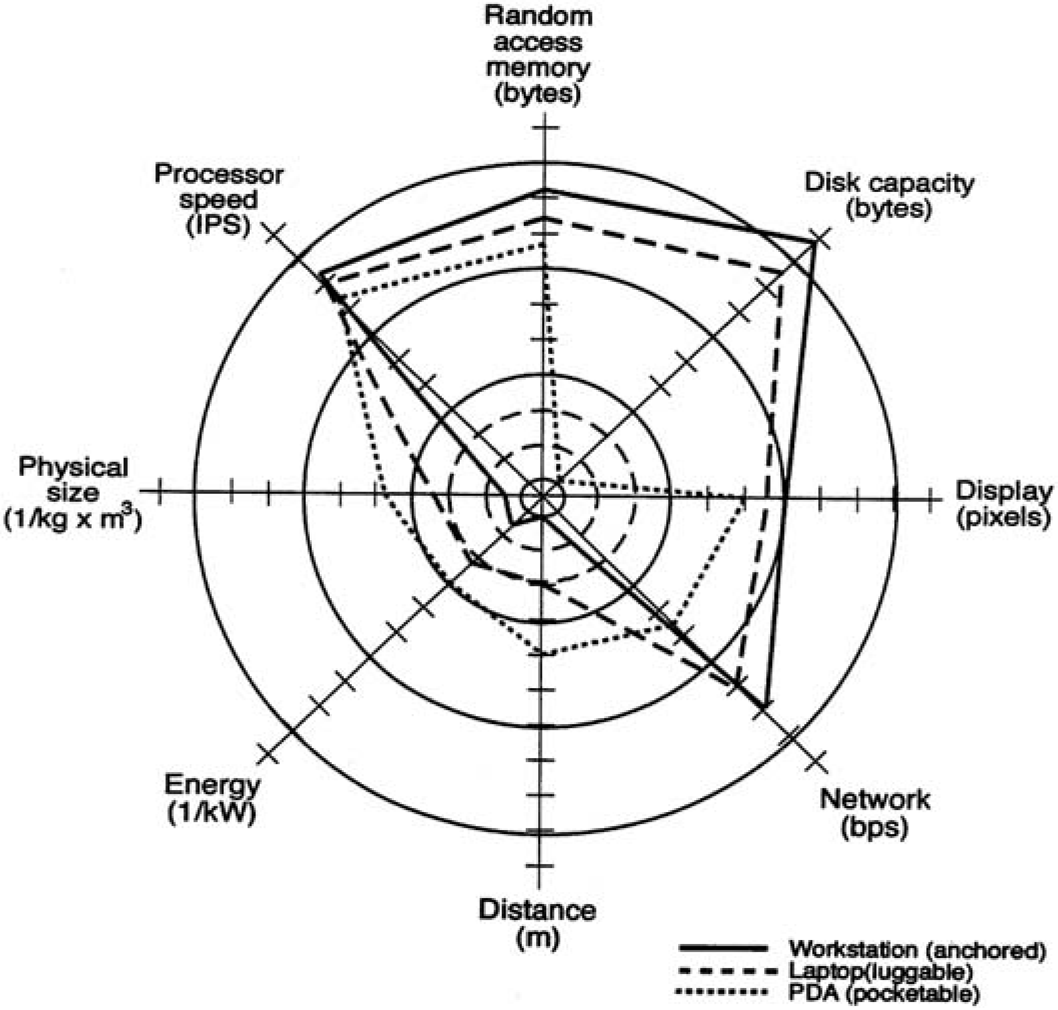


FIGURE 5-13 Computer system attributes. Each axis is a logarithmic scale with each mark representing a factor of 10 and each circle representing a factor of 1,000 (i.e., the value of the four circles are: one; one thousand; one million; and one billion from the inner most circle to the outer most circle).

General-purpose computing architectures achieve their general-purpose attributes at the expense of system complexity and energy consumption. Appendix E describes the evolution of wearable speech-operated computers from general-purpose laptop computers. The Navigator series of wearable computers, developed under DARPA sponsorship, demonstrates that it is possible today to implement software-driven systems with COTS (commercial-off-the-shelf) PC components, with one-half to one-fifth the energy consumption of a general-purpose computer.

Another DARPA project relevant to Land Warrior, a customized multimedia terminal using "embedded" systems, is described later in this chapter and offers improvements in energy efficiency by a factor of 100. Both cases illustrate what can be achieved in energy efficiency when performance is optimized for target applications and general-purpose characteristics are restricted.

Embedded systems are computer-based systems designed to provide specific required functions. They can be significantly less complex than general-purpose computer systems, and, by not requiring adherence to a complex complement of operating and application software standards, they can take advantage of a wide range of energy conserving techniques.

Industry experience with high performance portable consumer electronics, such as cellular telephones and camcorders, has shown that embedded computer systems can operate at 10 to 100 times less power than systems based on conventional general-purpose computers. Figure 5-2 plots the complexity of pagers and cellular telephones. The complexities of these entire systems approaches those of the microprocessor alone in general-purpose systems (see Figure 5-1), and yet they have power drains that are 100 to 1,000 times lower than those of general-purpose microprocessors. In addition to this power advantage, they can also be sized to the application by restricting performance to whatever is required to perform specific tasks.

Embedded systems are composed of one or two chips upon which a processor core is integrated with memory and with special-purpose processing elements, such as digital signal processors. Although microprocessors targeted for PC applications show little improvement in energy consumption, processors designed for embedded systems, such as the ARM™ processor (see Figure 5-6), are continuing to reduce the power drain per MIPS. For example, the ARM™ processor provides 185 MIPS for 450 mW with a 1.65 V power supply, yielding about 2.5 mW per MIPS.

The computational elements carried by the dismounted soldier could be based on embedded systems technology that optimizes the performance and energy usage of the human-portable systems. Over and above the significant reduction in energy consumption, use of embedded systems will lead to simpler human-computer interfaces that are easier to understand and quicker to use, thereby reducing the duty cycle and saving energy. In addition, the time, energy, and dollar costs associated with maintaining and upgrading software will be eliminated. Industry experience has shown that the cost of upgrading and maintaining software for a desktop personal computer can equal or exceed the purchase price of the computer each year.

New circuit concepts, such as adiabatic circuits, are being considered that may drive energy consumption in computing even lower in the next decade. Depending on the level of performance, these concepts may be applicable to future Army systems.

Design of a Low Power Soldier Terminal Using Embedded Systems

A computer-radio terminal capable of supporting the multimedia data services required by the Army could be designed using an embedded processor in which the high-computation-rate functions are implemented as energy-efficient dedicated CMOS integrated circuits. This implementation would reduce energy use for a specific function by 3 to 4 orders of magnitude compared with general-purpose components.

A multimedia terminal designed under DARPA sponsorship draws only 5 mW at full power (Chandrakasan et al., 1994). The project, which has been under way for about five years, is intended to demonstrate the energy savings of using dedicated processing for a device (called Info Pad) that provides multimedia capabilities of the kind needed on the digital battlefield. The terminal provides portable voice communication to the user, access to a wide variety of information and computation services, and support for wireless communications. Figure 5-14 summarizes the functions of the terminal, which include the interface to a high speed wireless link, text with graphics output, simplified user interfaces (such as pen input and speech I/O), and support for video displays.

Minimizing energy consumption in the multimedia terminal required a design optimized for energy, not only at the technology and circuit levels, but also at the levels of architectures, algorithms, and computing system partitioning. The multimedia terminal project illustrates that enormous savings can result when energy consumption is the major system design consideration.

Computing System Partitioning for Low Power

The multimedia terminal will be connected through a wireless link to the squad leader. This arrangement minimizes power requirements at the system level by partitioning computational tasks among the portable soldier terminal and other remote computing resources on the network. In the battlefield environment, the soldier terminal will not always be connected, but the system architecture is designed to minimize energy consumption when connectivity is possible.

Clearly the highest level of system optimization, and the most effective strategy for reducing power in the terminal, is to remove the general-purpose computer from the portable device. Data compression and decompression functions would need to remain in the terminal to reduce transmission costs, but other non-I/O-related computation would probably be performed better by computation resources with greater energy supplies.

As designed, the multimedia terminal will transmit audio and pen input from the user to the network on a wireless uplink and will receive audio, text, graphics, and compressed video from the backbone on the downlink. General-purpose functions will be performed by servers on the backbone network so the terminal electronics only have to provide the interface to I/O devices, as shown in Figure 5-15 (Chandrakasan et al., 1994). The increase in energy efficiency made possible by this system level partitioning of functions is enormous.

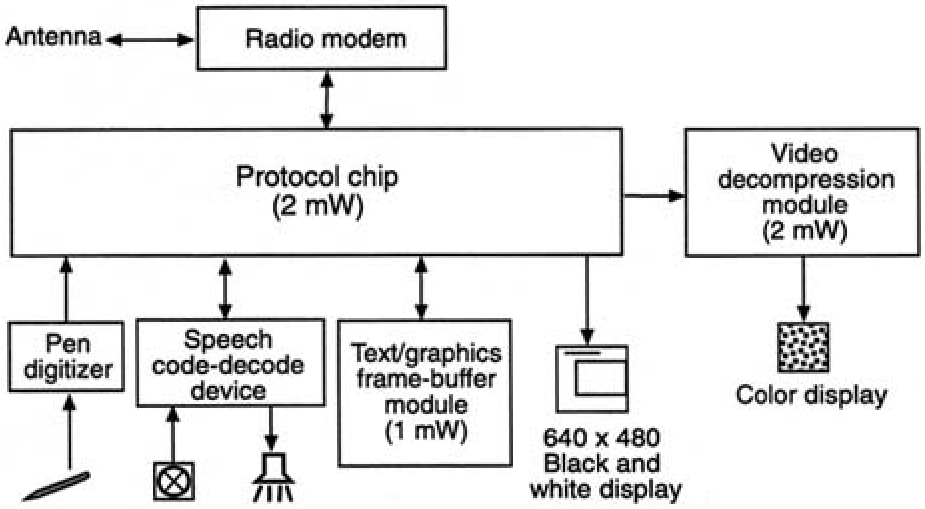


FIGURE 5-14 Functions of the multimedia terminal, including the interface to a high speed wireless link. Source: Chandrakasan and Brodersen, 1995b.

In the terminal design, six energy optimized special-purpose chips provide the interface between a high speed digital radio modem and a commercial speech codec, pen input circuitry, and LCD (liquid crystal display) panel displays. These chips also provide protocol conversion, synchronization, error correction, packetization, buffering, video decompression, and digital-to-analog conversion. The total power requirement for these electronic functions, when operating at a supply voltage of 1.5 V, is less than 5 mW, even while operating continuously.

The multimedia terminal project confirms that the power requirements of the Land Warrior system could be reduced by moving away from a design concept based on general-purpose computing and toward a concept based on customized embedded subsystems.

User Interfaces

The user's interface to the computer greatly affects energy consumption. The Land Warrior computer design should merge the users information space with the operational space. The system should offer seamless integration of information processing tools with the battlefield environment. To accomplish this, Land Warrior must offer natural and unobtrusive functionality, allowing the soldier to dedicate attention to the task at hand, with no distractions from the system itself. Conventional methods of interaction, including the keyboard, mouse, joystick, and monitor, all require some fixed physical relationship between user and device and are not conducive to efficient battlefield operations.

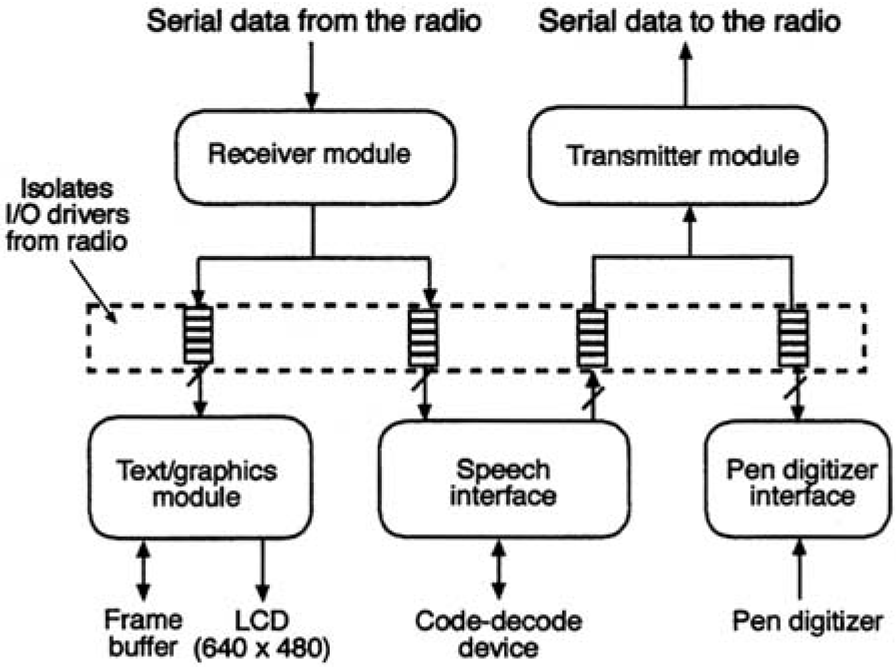


FIGURE 5-15 I/O device interfaces. Source: Chandrakasan and Brodersen, 1995b.

Human interface design is one of the most challenging problems facing Land Warrior designers. As computing devices move from the desktop to more mobile environments, many conventions of human interfacing developed primarily for office environments must be re-evaluated for effectiveness. How does the mobile system user best supply input while performing tasks that preclude the use of a keyboard? What layout of visual information most effectively describes system state or task-related data? To maximize the effectiveness of Land Warrior in mobile environments, the interface design must be carefully matched with user tasks. By constructing mental models of user actions, interface elements can be chosen and tuned to meet the software and hardware requirements of specific procedures.

The efficiency of the human-computer interface is determined by the simplicity and clarity of the mental model suggested by the system. By modeling the actual task as well as the human interface, a link can be established between user and machine that can then be examined to improve overall efficiency. The mental model of the interface design must closely parallel the model of the user task, and there must be minimal interference or obstruction by the computer to completing jobs.

Although few quantifiable metrics for evaluating interfaces are available, some basic observations can provide a means for comparison. One characteristic of an application interface is the number of user actions required to perform a given subtask. A subtask can be defined as an operation, possibly consisting of multiple inputs, that a user completes in the process of performing a larger coherent task. For example, in making an inspection, a user might wish to return from the present location in an application to the main menu. This subtask may require a single input (perhaps a voice command or an on-screen button) or multiple inputs (backing out through a hierarchy of categories to reach the top or main level). An application that requires few inputs will allow a user to dedicate more attention to the job at hand; a larger number of inputs will require more concentration on the computing system. A comparison of equivalent subtasks in two mobile computers is shown in Table 5-4 (Smailagic and Siewiorek, 1996).

A speech recognition engine accepts complex commands and enables a series of manual inputs to be executed with a single phrase. However, the response time to a spoken input is longer, and the accuracy is lower. For these reasons, the quantitative aspect of system latency and accuracy must be considered. In evaluating computer output displays, a National Research Council report, Tactical Display for Soldiers: Human Factors Considerations, addressed the impact of information presentation on stress and workload and warned that the wrong presentation format may result in "shifting the infantry soldier's attention away from the battlefield toward a computer-generated display may compromise situation awareness and increase workload" (NRC, 1997).

Another way that the user interface can be evaluated is by its ease of use. This characteristic is difficult to quantify because it is so closely associated with human reaction, but there are at least three basic functions related to ease of use: input, output, and information representation. Table 5-5 summarizes several points for each of these basic functions. Note that, unlike the continuous variable metrics for capacity and performance, the ease of use metrics are discrete.

Like the metrics for capacity and performance in Table 5-2, the ease-of-use metrics in Table 5-5 are also moving out with time. For example, the keyboard with an alphanumeric display using textual information is representative of time-sharing systems of the early 1970s. The keyboard and mouse, graphical output, and iconic desktop are representative of personal computers of the early 1980s. The addition of handwriting recognition input, speech synthesis output,

TABLE 5-4 Comparison of the Number of Steps Required to Retrieve Information Using Selection Buttons and Speech

	Buttons/Menu Selection	Speech
Get information	4	1
Get photograph	5	1
Navigate to location	3	2

TABLE 5-5 Ease-of-Use Metrics

Input	Information	Output Representation
Keyboard	alphanumeric display	textual
Mouse	graphical display	iconic
Handwriting recognition, speech recognition	speech synthesis	multimedia
Gesturing, position sensing	stereographic visual, audio	3D, virtual reality

and multimedia information emerged in the early 1990s. It takes about a decade to completely assimilate new input, output, and informational representations. By the early part of the next decade, speech recognition, position sensing, and eyetracking should be common inputs. Head-up projection displays, discussed later in this chapter, should allow superposition of information onto the user's environment.

Different interface types require different computational resources. Table 5-6 lists the approximate computer performance needed to support a given user interface when implemented in software on a general-purpose computer (Dahbura, 1996). It is clear from Table 5-6 that user interface technology influences energy consumption.

Although the size, weight, and volume of electronics will continue to shrink, mechanical interface devices have a minimum "footprint." These devices will have to be oversized for ease of use for soldiers wearing gloves or other

TABLE 5-6 Computational Requirements to Support Various User Interfaces

Interface Type	Required Performance (MIPS)
Textual	1
Graphical user interface	10
Handwriting recognition	30
Speech recognition	150
Natural language understanding	1,000
Vision	10,000

protective clothing. Dials and selection switches have been effectively used in such environments (Smailagic and Siewiorek, 1996). Even though there is a limit to the user interface footprint, the thickness and weight of the electronics can continue to decrease. At the limit, the "computer" could be a flexible "sheet" attached with Velcro or even woven into the outer layer of clothing.

The way that information is represented and manipulated can affect the amount of time the soldier must focus on computer tasks. During this time, the solider cannot concentrate on more urgent battlefield tasks.

DISPLAYS

This section discusses the power requirements for displays, applicable display technologies, and research and development (R&D) issues.

Requirements

The Land Warrior ensemble incorporates a helmet-mounted display in the integrated helmet assembly subsystem (IHAS), a weapon-mounted display in the integrated sight module (ISM), and a hand-held display tied to the vest.

Helmet-Mounted Display

The helmet-mounted display in the IHAS has the most stringent performance requirements of the three displays because its key functional requirement is to supply real-time imagery. Desired features include minimal energy consumption, high quality images for night operations, and situational awareness. Optimal situational awareness requires:

- wide field of view from imager (e.g., 60 degree field of view, which requires a minimum resolution of 2,048 × 2,048 pixels for a 20 mm display [Crawford, 1996])
- see-through viewing capability
- peripheral vision wherever possible

In the initial Land Warrior concept, an image intensifier is planned to provide imagery on the IHAS. In the long term, however, the image intensifier will be replaced because it cannot be easily scaled up to the higher resolutions needed for a wide field of view.

Weapon-Mounted Display

The weapon-mounted displays have included cathode ray tubes (CRTs), active matrix liquid crystal displays (AMLCDs), and active matrix electroluminescent

(AMEL) displays. Peripheral vision is not as important for the weapon-mounted display, which is used in a monocular fashion for sighting targets, rangefinding, and pointing. The performance required is similar to that of the viewfinder in a commercial camcorder, except the resolution must be higher the 320×240 pixels typical of camcorders.

Hand-Held Display

The hand-held display is the most expensive of the three Land Warrior displays in terms of energy consumption. The key function of the hand-held display is to display maps, written communications, and other high resolution data. There is a basic physical limitation to the overall energy-efficiency that can be obtained by all displays designed to be radiated into 2^{π} steradians. Only a small fraction $\frac{2\pi a^2}{2\pi R^2}$ is actually subtended by the eye of the viewer. Here a is the radius of the pupil of the eye (approximately 0.1 cm for daylight and 0.5 cm for nighttime background illumination), and R is the distance separating the center of the display screen from the center of the pupil (about 3 cm for a helmet-mounted display and 30 cm for a hand-held display screen). As a consequence, the best one can achieve is for the viewer to capture 3 percent of the radiated image energy in nighttime conditions with a helmet-mounted display. When a hand-held flat panel display is used at a 30 cm separation, the energy capture efficiency degrades to 0.03 percent.

Current and Future Technology

The principal function of a display is to convey information. Energy expended to display information that is not conveyed is wasted energy. Human factors research shows that, in optimizing situational awareness, the format of messages is just as important as the content or visual quality. In particular, studies have found that text tends to distract the viewer from awareness of the surrounding environment. Analog content, such as imagery and display symbols are not as distracting. Compared to a binocular system, the proposed monocular viewer for the IHAS is not energy efficient (NRC, 1997).

Displays will have to be in both the flat panel format for mission planning in the field and in the eyepiece configuration for the ISM and the IHAS modules. The power requirement for the flat panel displays, the more difficult of the two to reduce, can be relaxed in the near term if the duty cycle for use in the field is kept below 5 percent. The head-up display and the weapon-mounted display, on the other hand, are expected to be in use at least 50 percent of the mission duration in many scenarios. Therefore, the need to reduce energy consumption in the near term is more urgent.

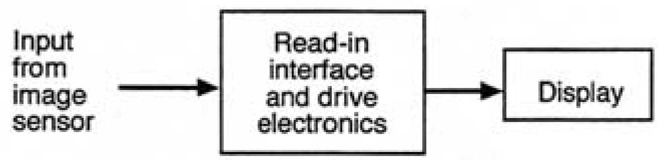


FIGURE 5-16 Block diagram of a display and associated electronics interface.

The display modules are important interfaces for the IHAS, the ISM, and the Land Warrior computer. Figure 5-16 is a generic block diagram showing the normal display configuration, consisting of a read-in interface, associated drive electronics, and the display itself.

Helmet-Mounted Display

Several trends are helping to reduce the power required by displays in portable systems. Initially, display technology was highly inefficient, especially in backlit displays, in which less than 0.5 percent of the fluorescent backlighting was used as part of the display luminescence and the rest was wasted. Through a series of refinements, the AMCLD, AMEL display, field emission display, and alternating current plasma display technologies have improved the efficiency of backlighting by almost two orders of magnitude.

Currently, the AMEL display incorporated in the helmet-mounted display on the IHAS requires that a fairly high voltage be applied across the display (65 to 200 V). Conversion losses are inevitably associated with the step up to the higher display voltage from the standard output voltage of the battery. Until recently, this would have been a major problem, but the losses associated with DC-DC power conversion can be minimized through clever circuit designs (Chandrakasan et al., 1994). Thus, the combination of AMEL display technology and high-efficiency DC-DC converters have reduced the energy consumption from 1.4 Wh to a respectable 0.32 Wh of energy dissipation in the nighttime display and 0.20 Wh in the daytime display.

Weapon-Mounted Display

Because of cost considerations, the current ISM display is a CRT requiring 1.3 W of power, 400 mW for the display, and 900 mW for the drive electronics. In investigating the conversion from a CRT technology to photolithographically produced electroluminescent displays, a redundancy was noted in having both a display and a frame buffer, when the AMEL itself can function as a frame buffer.

Therefore, some of the recent display subsystem concepts under consideration by the Army eliminate both the frame buffer and the analog-to-digital conversion step from the imaging camera, so that the analog output of the camera is read directly into the display. These two modifications would drop the power requirements from 1.3 W to 0.25 W. In the long run, AMLCD displays similar to those needed for the weapon-mounted display are being developed in the commercial arena for use as video camcorder viewfinders with typical drive powers of 0.5 W. Commercial investment in this technology is likely to drive down the cost and energy consumption of these devices.

Hand-Held Display

Hand-held displays should also benefit from developments in commercial technology, especially those aimed at the pager, cellular telephone, and electronic organizer markets. With an anticipated duty cycle of 5 percent or less, the hand-held display can readily achieve reductions in energy consumption through the addition of power management circuitry. Careful design of the interface and drive electronics should also significantly reduce the drain on the batteries. Finally, there is a move towards a cholestric liquid crystal display (ChLCD) technology, which does not require constant refreshing at a 60 Hz frame rate, only consumes energy when changing the display image, utilizes reflected light to give the optical appearance of paper, and can hold an image for months at a time using negligible power (Crawford, 1996). Although this technology is not very useful for the IHAS display or the ISM display, where full color or full motion video speed are desired, it is ideal for the display of digitally formatted data, text, maps, and other high resolution graphics. In its current form, the ChLCD is not backlit, thereby circumventing the heavy losses associated with the eye not capturing all of the display radiation. However, military requirements tend to demand both day and night capability, so some form of lighting must be conveniently available to illuminate the display. Recent advances in the use of electroluminescent light (such as the illumination in INDIGLO™ watches) may have to be incorporated into the ChLCD display.

Future Research and Development

The state of the art in the read-in interface can clearly be improved through the introduction of carefully designed ultra-low power electronics (ULPE) and power management techniques. However, physical limitations will restrict how much the energy consumption in flat panel displays can be reduced, especially the backlit architecture.

TABLE 5-7 Radiated Energy Captured by the Viewer

Display Type	Daytime (worst case) 0.1 cm Diameter Pupil (%)	Nighttime (best case) 0.5 cm Diameter Pupil (%)
Helmet-mounted display	0.1	3
Hand-held display	0.001	0.03
Virtual retinal display	~100	~100

Because "see-through" displays improve situational awareness, the virtual retinal display is a highly energy-efficient, long-term candidate for insertion in the Land Warrior system (Inside the Army, 1996). The high efficiency is due to the fact that nearly 100 percent of the light emitted by the display is captured by the eye, unlike flat panel displays, which by design emanate into 2π steradians so that they can be viewed from any angle. In addition, proper design of the mechanical mounting fixture can minimize obstruction of the field of view. Because the laser diodes can be operated at the standard CMOS operating voltages, and the operating currents can be designed to work at tens or hundreds of μA, the power required to operate the lasers is very low, less than 500 μW.

In fact, one would expect the power requirements for a virtual retinal display to be dominated by its drive electronics and the scanning mechanism. The former could be minimized through the application of standard ULPE design and power management techniques, and the latter could be accomplished either by acousto-optic deflection of the optical output or by using microelectromechanical parts, whichever proves to be more reliable and efficient. Table 5-7 summarizes the anticipated energy capture efficiency by the viewer using each of the three display technologies.

In summary, three development trends are helping to bring down the energy consumption characteristics associated with displays:

- improvements in backlighting efficiencies
- improvements in DC-DC voltage converter efficiencies
- system-level redesigns of the display subassembly to achieve optimal energy conservation within the context of the function

Future technology requirements unique to the Army include low power, high-pixel-density, video-quality displays to support improved situational awareness with wide field of view on the helmet-mounted display and with resolution sufficient for positive target identification on the weapons sight. Commercial technology trends should support Army requirements for higher resolution and lower refresh rate on hand-held displays. However, the 320 × 240 resolution typical of commercial imagers will not be adequate for the Army's target recognition requirements. Consequently, even though commercial investment in this technology is likely to drive down the cost and energy consumption of these devices, the military will still have to invest to achieve higher resolution.

SENSORS

The combined purpose of the sensor suite is to improve the situational awareness of each soldier to enhance his or her lethality and survivability. In addition, Land Warrior will extend the command and control capability by supporting real-time target location and call-for-fire and by supplying sensor information up the chain of command to improve decision making. For example, data from signals intelligence, chemical detectors, and laser sensors may paint a more accurate picture of a threat as it develops. The sensor suite deployed with the dismounted soldier must also be optimized in design and performance to minimize the drain on energy resources thereby extending battery life and reducing the number of backup batteries required to complete a mission.

A range of sensors is thought to be useful for deployment in support of the dismounted soldier. Currently, many of these modules require excessive amounts of power, as can be seen in Table 5-8. One of the by-products of the campaign to

TABLE 5-8 Land Warrior Sensor Suite Power Requirements

Function	Cumulative Peak Power (W)	Function Operating Power (W)	Standby (Alert) Power (W)	Operating Duty Cycle (%)	Average Operating Power (W)	Projected (2015) Goals for Average Operating Power (W)	Projected (2015) Two-Week Mission Goals for Energy Use (Wh)
GPS	1.80	1.50	0.60	45	1.00	0.001[a] (0.020)b	0.168
Video camera	1.20	1.00	0.00	15	0.20	0.008[c] (0.050)b	1.340
ISM[d]	7.80	6.00	0.00	Table 5-9	2.80	0.094	15.800
IHAS[e]	5.80 (night)	5.60 (day)	0.25	Table 5-10	2.80	0.075[f]	4.200[f]

[a] Numbers obtained from Stanford models on GPS design; assumes 5 percent duty cycle

[b] Power required before accounting for duty cycle

[c] Assumes color and high resolution upgrades

[d] See Table 5-9

[e] See Table 5-10

[f] Assumes development of virtual retinal (VRD) color display

Source: Efkeman, 1996.

minimize the power requirements of these sensors and other electronic aids is a reduction of the soldier's electronic signature, which will improve survivability. Other by-products are a reduction in battery weight and lighter, more compact sensors. This is important because every pound saved in battery weight or in the accompanying sensor suite translates directly into ammunition or food the soldier can carry.

Only the sensors appropriate for a particular mission should be carried. This will require a modular system, one that would also facilitate later upgrades of sensor technologies. As the technology advances, one is likely to be able to improve energy efficiency by including different sensors within an integrated assembly, as has been done with the IHAS and the ISM.

Table 5-8 lists power requirements for the current Land Warrior suite of sensors. Detailed breakdowns for the integrated IHAS and ISM are shown in Tables 5-9 and 5-10. Except where noted, the projections of future performance for these electronics assume that current power levels are obtained by using 5V commercial CMOS technology and standardizing to a common voltage wherever possible. Note that improvements projected for the IHAS in Figure 5-10 are achieved by scaling to decreasing drive voltages. This implies a need to be alert for and to develop technologies that are voltage-compatible with commercial CMOS whenever possible.

Additional reductions in energy consumption are possible by introducing power optimizing hardware and software design methodologies. However, it should be emphasized that these design trade-offs should be made in the context of a top-down evaluation of the overall system. Although the tables and the discussion in this chapter focus on ways to minimize energy consumption in the

TABLE 5-9 Integrated Sight Module (ISM) Power Requirements

Function	Function Operating Power (W)	Operating Duty Cycle (%)	Average Operating Power (W)
Controller	1.265	50	0.633
Direct view optic (DVO)	0.075	10	0.008
IR sensor processor	2.425	50	1.213
Thermoelectric cooler (TEC)	0.100[a]	50	0.050
Display	1.300	50	0.650
Regulator	0.360	50	0.180
Compass	0.350	10	0.035
Laser rangefinder	~0.05	10	0.005
IR pointer	0.075	10	0.008
TOTAL	6.00	—	2.78

[a] Assumes operating temperature extremes of -32°C to +49°C.

Source: Marshall, 1996.

individual subassemblies deployed with Land Warrior, effective optimization of the system must involve a top-down evaluation.

TABLE 5-10 Integrated Helmet Assembly Subsystem (IHAS) Power Requirements

Function	Function Operating Power (W)	Operating Duty Cycle (%)	Average Operating Power (W)
Day display	0.200[a]	50	0.100
Night display	0.320[a]	50	0.160
Display electronics module			
Video board (including AC power converter)	4.000	50	2.000
Miscellaneous electronics board	0.120	50	0.060
DC power conversion module	0.610	50	0.305
Laser detector	0.600	50	0.300
Imager	0.100	50	0.050
Total			
Day	5.63	—	2.82
Night	5.75	—	2.88

[a] Assumes AMEL display.

Source: Doney, 1996.

In general, one can predict the drop in power requirements (assuming everything else remains fixed) by scaling the drive voltage. The ISM, IHAS subsystem, and the GPS module incorporate analog technologies that do not scale with the square of the voltage and are exceptions to this scaling rule. Other ways to reduce power are discussed in the following sections.

Because all of the functional requirements have not been defined for the laser detector, a conservative estimate of its initial power requirement was assumed to be one-tenth that of a full imaging array. In fact, this number will probably be much lower because the laser detector should not require an analog-to-digital converter.

Microelectromechanical Systems

Microelectromechanical systems (MEMS) are used in photolithographic technology for the fabrication of high-aspect-ratio (100:1) microscopic structures. MEMS technology may also apply to the micromechanical turboalternators discussed in Chapter 3. The addition of MEMS structures in the sensor modules would enhance functionality, lower cost by achieving economies of scale, and reduce energy consumption. In particular, the fabrication of microbolometers with MEMS technology is expected to improve the image resolution of infrared sensor arrays by eliminating cross talk among the adjacent sensor pixels.

MEMS could also be used to implement sensor mechanisms with moving parts, such as microshutters; microchoppers for the infrared sensors; chemical sensors, such as miniature mass spectrometers ("electronic noses"); and micromechanical beam writing scanners for the virtual retinal display. MEMS technology may also apply to micro-machined oscillators, filters, diplexers, and switches used in radio communications.

Currently, there is no MEMS technology road map like the NTRS (discussed in Chapter 4). However, the list of potential mass market commercial applications for MEMS is growing rapidly. By the year 2,000, it is estimated that the MEMS worldwide market will be nearly $14 billion and will enable almost $100 billion in new or improved systems (SPC, 1994). The biggest markets will be in the automotive and medical fields. This compares with a projected market for high-definition television (HDTV) of $7.1 billion in the year 2000. Thus, it is very likely that by 2001, the MEMS application base will have grown large enough to warrant an industry road map. This will significantly lower the cost for many of the MEMS technologies the Army will need.

Infrared Sensor Arrays

Several infrared wavelength bands are important to military imaging applications. They have different strengths for imaging in terms of sensing the surrounding environment. The bands are 1 to 2 µm; 3 to 5 µm; and 8 to 12 µm.

The 1 to 2 µm band is used for laser detectors to sense and warn soldiers when lasers or other infrared targeting optics are being used. The other two bands are more likely to be used in imaging applications because they can provide imaging capability for both day and night missions. However, many complex issues must be considered in selecting one or the other, including the fact that the 8 to 12 µm band detects a higher radiance from the scene, while the 3 to 5 µm band offers higher contrast. Some of these sensors require cooling or temperature control; others are uncooled but still require ±0.05°C temperature stabilization at the operating temperature to ensure noise equivalent temperature differential (NETD) values of 0.1°C.

Figure 5-17 is a block diagram of a generic imaging array and associated electronics. In both the cooled and uncooled sensors, very little energy is consumed by the imaging detector array itself. Traditionally, the temperature controller circuitry, the readout interface, drive electronics, and analog-to-digital converters dissipate most of the energy. In addition, the earliest version of the cooled sensors required a significant amount of power to maintain cryogenic temperatures.

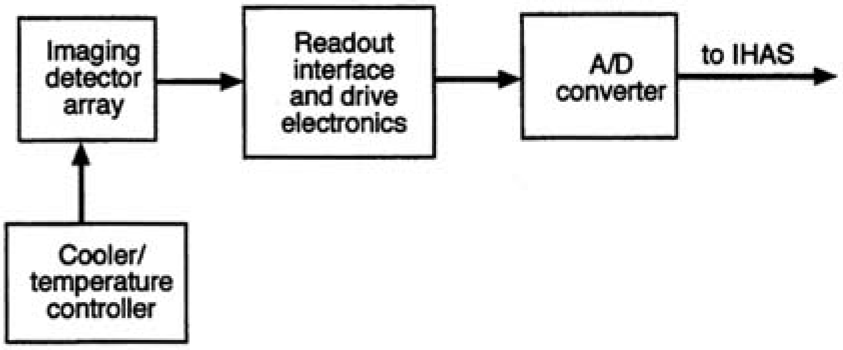


FIGURE 5-17 Block diagram of a generic imaging array.

Temperature Stabilization

The physical limits of minimizing power requirements with cooling technology is driven by the temperature differential that must be maintained between the ambient environmental temperature and the sensor's operating temperature, according to the expression:

$$q = -\kappa A \frac{dt}{dx}$$

where *q* is the heat to be dissipated at the cold face of the thermoelectric cooler, is the thermal conductivity, *A* is the area, *dt* is the temperature difference between the hot face of the TEC and the cold face of the TEC, and *dx* is the thickness of the heat sink (i.e., the TEC thickness). Although both heating and cooling capabilities are required by military specification to stabilize a sensor over a given temperature range, this discussion will focus on cooling because it is less efficient than heating.

Optimal cooling efficiencies are obtained when TEC modules are run at a small percent of their operating maximum and when the thermal temperature differences across the cold and hot faces of the module are small. This is accomplished by:

- lowering the heat load of the electronics by reducing energy dissipation
- keeping the difference between the temperature of the sensor head and the ambient temperature small

By overdesigning so that the TEC cooling capacity is a small fraction of the heat loads, cooling efficiencies of 75 percent or better are achievable (MacLannon, 1997). This realization led to a significant shift away from cryogenically cooled detector arrays to temperature controlled bolometers that operate near room temperature. This means that sensor cooling power will only be required to maintain control over small temperature shifts from room temperature (5°C≤Δ≤10°C offset from the ambient temperature) instead of the 223°C temperature differential required for cryogenically cooled systems. The power requirement is expected to be reduced from the 1,000 mW peak value associated with temperature extremes in the MILSPEC range for cryogenically-cooled systems to the nominal 100 mW of power indicated in Table 5-9.

Two candidates are under extensive development by the Army (Flannery and Miller, 1992):

- capacitive bolometers made of barium strontium titanate (BST) in the 3 to 5 µm band
- resistive bolometers made of vanadium oxide in the 8 to 12 µm band

The resistive bolometer sensors employ a bridge technology that thermally isolates the resistive film on a thin mechanical bridge so that large NETDs can be sensed for thermal differentials as small as 0.1°C. The capacitive or ferroelectric bolometer technology operates on a similar principle, except that it is continuously chopped (resistive bolometers need to be periodically shuttered every 15 minutes or so to recalibrate the system). Capacitive bolometers are also moving towards microbridge technology in an effort to minimize cross talk caused by thermal diffusion among adjacent pixels; this would reduce the extent to which the image resolution is limited by optical components.

Future Research and Development

The fundamental technology common to both resistive and capacitive bolometers is the MEMS high-aspect-ratio fabrication technology. Currently, process yields in MEMS are not very high, yet high yields are vital to keeping costs of high-density imaging arrays down. The Army will have to give a high priority to supporting the development of these sensor arrays, at least until MEMS acquire a large enough commercial base to justify the definition of a MEMS technology road map. Coupling this progress with improvements in thin-film deposition may pave the way for long-wavelength detector arrays that do not require active temperature stabilization to a fixed temperature but can be stabilized against an ambient background. If the fabrication problems can be solved, thermocouple junction thin films have the added advantage of generating an internal voltage, which eliminates the need for an external power source.

Ultra Low-Power Electronics for the Sensor Interface

The active pixel sensor (APS) is a second-generation, monolithic sensor with one or more active transistors per pixel, which enables development of low-power, low cost, highly miniaturized instruments for use in space missions.

Unlike the widely used charge coupled device (CCD) imagers, APS sensors do not require repetitive charge transfers and therefore do not require special fabrication technology. APS, as developed at the Jet Propulsion Laboratory (of the National Aeronautics and Space Administration), is fabricated by commercially available CMOS technology, enabling implementation of highly integrated "camera-on-a-chip" imaging systems (Dickinson et al., 1995; Nixon et al., 1996) Unlike CCD, a CMOS APS is a random access, low capacitance device. Furthermore, use of CMOS technology allows integration of on-chip timing and controls with the APS. The resultant imager system-on-a-chip exhibits ultra-low power requirements (more than a 100-fold reduction compared to the state of the art) and extensive miniaturization (more than tenfold reductions in mass and size). Integration of on-chip electronics for camera timing and control, signal conditioning and noise shaping, analog-to-digital conversion, and interface definition leads to imaging systems with extremely high performance (low noise, high functionality, high speed, high reliability, and ultra-low power requirements.)

A CMOS APS operates from a single 5 V (or 3.3 V) supply and features large format (1024×1024), high resolution (< 12 μm pitch), wide dynamic range (more than 75 dB), digital I/O, random access readout, low smear, antiblooming control, and electronic shuttering, with excellent imaging performance (quantum efficiency similar to interline CCD, and noise < 12 e- r.m.s.). It enables visible imaging in many different formats. The total system power requirement is far lower than the requirement of the analog-to-digital converter alone in a conventional imaging system because there is no need to drive the analog signal off the chip before the converter.

Because APS arrays are completely silicon-based, including the detectors, they respond in the visible and near-infrared (0.4 μm to 1.0 μm) wavelengths and fall outside the wavelength bands of key interest to the Army. Nevertheless, the lessons of this commercial technology have led to lower power consumption and lower costs in interface electronics, which can be translated to improvements in similar interfaces on infrared detector arrays. The challenge will be to find ways to achieve single-chip integration of the detector materials that can sense the longer wavelength radiation bands (3 μm to 5 μm; and 8 μm to 12 μm) by developing thin-film deposition techniques for both BST and vanadium oxide, the materials used for uncooled detectors.

Indeed, a long wavelength vanadium oxide microbolometer focal plane array based on commercial CMOS technology is available for both commercial and military use (Butler et al., 1996). The developers have integrated onto a single focal plane array features such as nonuniformity correction, auto gain and level correction, television video, and analog-to-digital converter output. The array is a 327×245 pixel array with a 10-bit analog-to-digital converter at a 6.1 MHz output data rate and a 60 Hz frame rate. It requires less than 500 mW of power, 250 mW of which is attributed to the analog-to-digital converter. Much of the energy savings in this display comes from standardizing to 5 V with commercial

CMOS and using an on-chip analog-to-digital converter. These numbers will improve with the push towards lower chip voltages.

Research and Development

Future R&D should focus on further reducing dependence on the TEC. In addition to ongoing work to improve the yield of capacitive and resistive bolometers, thermocouple bolometers for reducing the thermal offset energy consumption at the TEC should be investigated. Once MEMS fabrication techniques have advanced, microbolometer structures could be integrated onto chips with CMOS circuits without degrading CMOS performance. Ultimately, merging MEMS and CMOS should bring down the cost of these sensor systems. A commercial industry guideline similar to the NTRS should improve technology development.

Laser Detectors

Currently, a single laser detector mounted in a frontal position on the helmet is used for Land Warrior. This positioning does not optimize situational awareness because when lasers come into play on the battlefield, they will be used largely as a means of acquiring targets, whether tanks, trucks, or foot soldiers. Laser detection would be enhanced with sensor coverage in all four directions of the helmet and a sensor net on the soldier's vest. This would improve the soldier's chances of being forewarned when he or she has been targeted. Cloaking the soldier in a large number of surface-mounted detectors at various points on the vest and helmet, however, would be costly in terms of energy; the duty cycle for the laser detector will probably be 50 percent or more over the course of a mission. Furthermore, it is difficult to make sensors rugged enough to prevent damage in the combat environment.

One way to solve this problem would be to weave 100 or more lensed light collectors in the form of multimode fibers into the vest and helmet. By fusing the output ends of the fibers, their integrated output could be used to illuminate a common detector. Two common detectors, one located in the helmet and one in the vest, are illustrated in Figure 5-18. The embedded collectors could capture laser radiation from different locations and directions and feed it to a combination detector-amplifier. A network of optical collectors might also double as the backbone for an infrared wireless link between the helmet, vest, and weapon to handle data. Power requirements for the wireless communications interfaces needed to link the soldier subsystems are discussed in a later section in this chapter.

The heart of the laser detector technology is similar to the technology of infrared imaging arrays, i.e., a single detector with an adjacent preamplifier and ASIC (application-specific integrated circuit). One might locate three or four

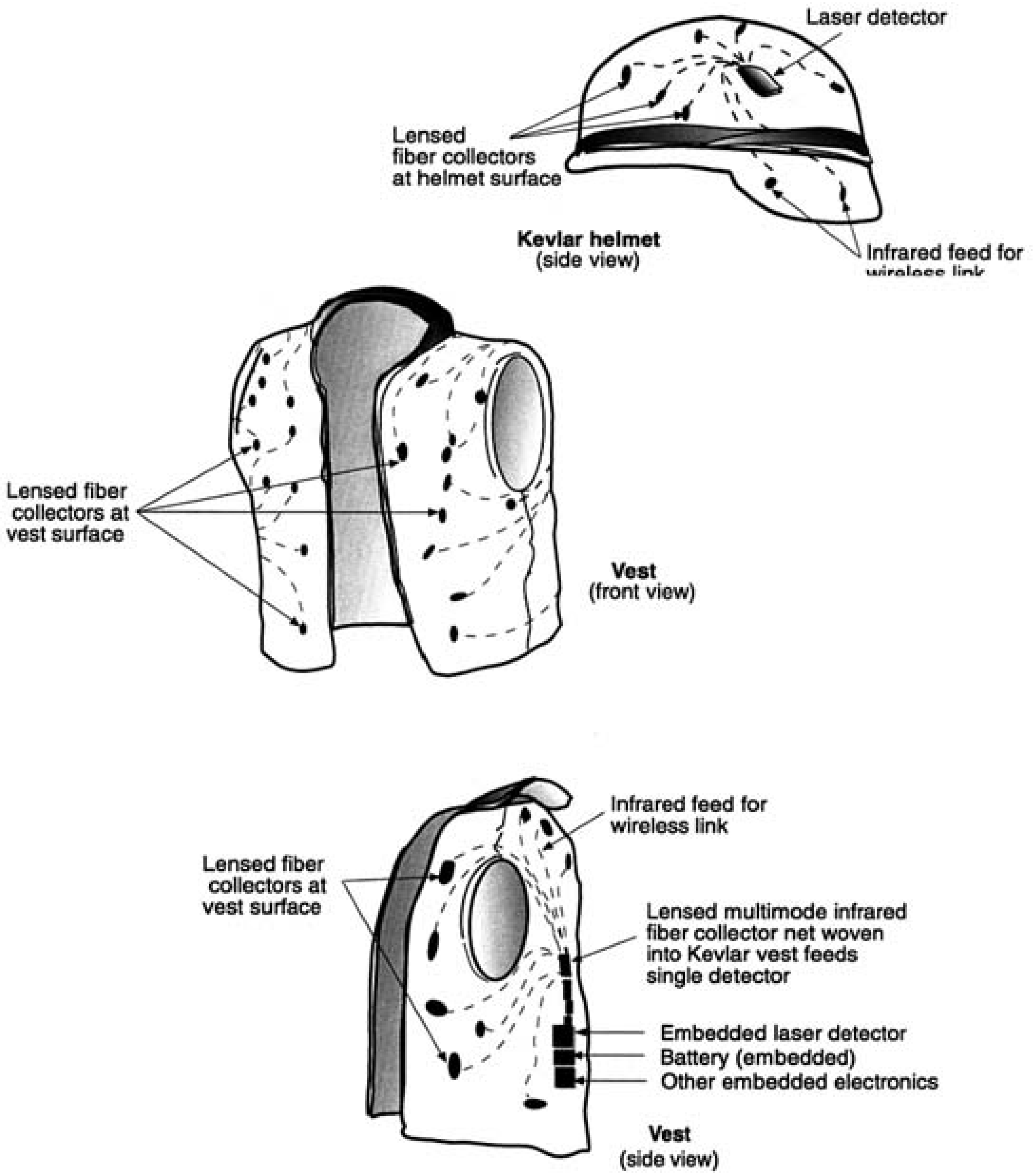


FIGURE 5-18 Soldier's vest and helmet with laser detectors.

detector-amplifier combinations on the same chip, each fed from a fiber bundle that recovers signals from a different direction (enabling the user to distinguish the general direction of the source). Other functions might be included on the chip to permit the user to measure wavelength and other signature information, such as pulse length. If the large infrared sensor arrays and their associated control and analog-to-digital converter electronics can be deployed requiring 50 mW of power using 5 V CMOS technology, the same technology applied to a single system would enable power requirements of less than 5 mW.

Research and Development

Weaving multimode fibers to serve as light collectors into the soldier's Kevlar vest and helmet material will require supporting technology development.

Laser Rangefinders and Infrared Pointer Technology

The minimum average optical output of the laser rangefinder is 1 mJ. This level is currently achieved with a diode-pumped solid state neodymium: yttrium lithium fluoride (Nd:YLF) laser with difference frequency shifted to an eye-safe wavelength of 1.5 mm. The rangefinder has a nominal operating power of 50 mW and peak power requirements of 750 mW in the Q-switching mode. Because the range to a target can usually be established with a single pulse, the duty cycle during peak power mode of operation is expected to be very low ($< 3 \times 10^{-5}$ percent). Consequently, energy consumption is dominated by the nominal operating condition. For the 50 mW quoted, the 5 percent duty cycle implies that the average power requirement over a 12-hour mission will be 2.5 mW.

In contrast, the infrared pointer is a light emitting diode operated in continuous-wave mode and has an output power of 1 mW. Its peak power requirement is 75 mW, and its 5 percent duty cycle implies that the average power required over a mission will be about 4 mW.

Laser Rangefinder

With diode lasers, it is possible to achieve 65 percent power conversion efficiencies from edge-emitting lasers, although 25 percent is typical of commercial lasers. Under the best of circumstances, one might also obtain 80 percent power conversion efficiencies in pumping the Nd:YLF laser with the diode laser and another 71 percent when converting from 1.06 μm to 1.5 μm. Naturally, the actual wavelength conversion efficiencies are considerably worse than this, so that most of the power requirement in the laser rangefinder is accounted for by converting the optical energy to the 1.5 μm wavelength. This rather complicated process for obtaining the 1.5 μm was used in the early stages of the Land Warrior because there were no direct diode sources of 1.5 μm that could supply energy pulses as large as 1 mJ. However, if the current trends in diode laser technology development continue, a 1.5 μm wavelength diode laser could be switched to achieve the 1 mJ per pulse requirement. Because p-n diode technology is one of the most efficient means of converting from electrical to optical energy, a direct diode replacement for the current arrangement would optimize the design in terms of power consumption. Given the current trends, an adequate R&D strategy would be to track this particular technology and convert to a direct diode laser source when it becomes available.

Infrared Pointer

For the infrared pointer, although the power requirement is dominated by the electrical-to-optical conversion efficiency, 10 mW of the total 75 mW of operating power is nonetheless attributable to the electronics interface with the computer. By using ultra-low power design strategies, the power required at this interface can be reduced below 1 mW. With respect to the electrical-to-optical conversion, the typical power conversion efficiencies of light emitting diodes (LED) are similar to diode lasers, but because of the radiation pattern, only a small percentage of the emitted light is subtended by the collection optics (6 percent with an optimized design for the collection optics). Thus, the optical conversion efficiency could be further improved by replacing the diode laser with an LED, which would reduce the power required to generate 1 mW of infrared radiation to approximately 4 mW and would result in a net total drive power of 5 mW for the infrared pointer.

Cost has been the major reason for selecting an LED over a laser diode in many applications, but costs are expected to fall as multimedia communications using high bandwidth fiber optics reach the mass consumer market.

Research and Development

High optical losses in the current prototypes will be offset to some degree by expected low duty cycles. Low average power requirements make R&D to reduce energy loss in the infrared pointers a low priority compared to losses due to other sensors. The optical conversion efficiencies are expected to continue to rise as a result of heavy investment in R&D by telecommunications companies and other companies concerned with users of multimedia and the internet. Commercial R&D will focus heavily on lowering the cost of the optical subcomponents. The Army stands to benefit from this commercial investment, although commercial interests will not be concerned with packaging these devices compactly to withstand the rugged environment of military operations.

Global Positioning System

The most common use of the GPS (global positioning system) by the dismounted soldier is for land navigation. GPS is also used in search and rescue operations, and there are plans to adopt it for precision delivery of cargo by parachute or paraglider. A major concern to the Army is the potential for primary interference from deliberate jamming or spoofing by an adversary or by friendly forces. Therefore, all GPS-based navigation systems must have one of the following features: sufficient jamming-to-signal ratio strength to navigate through the jamming environment; the ability to null out the jamming signal; or an alternative to GPS for navigating through the jamming environment. Full GPS accuracy would thus be denied to the enemy by selective availability and by antispoofing security procedures. The GPS receiver in the soldier's sensor suite must be capable of meeting all of these requirements.

The GPS receiver in the Land Warrior ensemble has two power management modes, continuous mode and fixed mode. In the continuous mode, the receiver is in continuous operation, and the battery is good for about 10 hours. In fixed mode, the unit is powered on once every 15 minutes, increasing the battery life to about 40 hours. Another power management option would be to activate the GPS only on demand because the average mobility of a foot soldier does not require continuous updates. The Army is also investing in a longer term program to develop an ULPE GPS module. Currently, GPS research is focused on three topics: integrated CMOS technology; low voltage front-end receiver circuits; and fast synchronization and reacquisition algorithms.

The operation of a GPS receiver involves three data acquisition phases: acquisition of the almanac information; acquisition of the ephemera information; and acquisition of phase synchronization. The almanac data takes at least 12.5 minutes to acquire and must be updated every few days. Ephemera information takes about one minute to acquire and must be updated about every four hours. Even though these two kinds of data take a long time to acquire—the low data rate of 50 bits per second still results in a duty cycle of less than one percent—the impact on energy consumption is not as important as the problem of phase synchronization. Therefore, attempts to reduce the power requirement for GPS have been focused on reducing the active power and the time required in phase synchronization (Meng, 1997).

To reduce the active power of a GPS receiver, the design of both analog and digital circuits must be optimized for low power. With recent developments in CMOS technology, highly integrated circuits can operate in the GHz range, which provides a low cost, low power solution to the problem. Based on a 0.35 μm CMOS design, a combined low noise amplifier and mixer operating at 1.6 GHz requires less than 7.5 mW with reasonable gain of 20 dB and less than 3 dB of noise figure (Shahani et al., 1997). The GPS front-end circuits can be implemented in less than 10 mW, using standard CMOS technology (Meng, 1997).

After the GPS signal has been converted to a low intermediate frequency on the order of a few megahertz (MHz) in the receiver, an analog-to-digital converter can be used to digitize the analog data to binary bits. A 2-bit converter operating at 20 Mhz requires less than 1 mW of power, which does not impose a power concern on the overall design (Meng, 1997).

A composite correlator architecture has been developed for GPS data acquisition to implement multiple-channel demodulation without incurring much overhead in power. As a result, the GPS receiver can perform 6-channel or 12-channel acquisition at a fairly low clock rate without the usual power penalty. The active power for data acquisition is estimated to be around 10 mW, assuming continuous operation (Meng, 1997).

The base-band signal processing for the calculation of positions and timing will employ dedicated low power digital circuits operating at 1 V supply voltage. Using dedicated hardware, flexibility is traded off for a reduction in power. Simulation shows that the power required for calculating positions and timing is negligible (less than 1 mW) because updated information is only needed once every few seconds (Meng, 1997).

Current GPS systems take at least 1 second to reacquire phase synchronization, to demodulate the received signal accurately, and to estimate the pseudo-range. Instead of using the standard early-delay loop for this purpose, a phase-error interpolation scheme was developed that requires only a fraction of a second for accurate phase synchronization. By employing this new phase-lock algorithm, the overall average power, or the duty cycle, is reduced. For example, to monitor a position continuously, the GPS may have to be turned on every 2 seconds without losing bit synchronization. If it takes only 100 milliseconds, instead of 1 second, for phase synchronization, the total energy dissipation will be reduced by a factor of 10, regardless of the actual active power (Meng, 1997).

A single-chip GPS receiver fabricated in the standard 0.35 CMOS technology that requires less than 20 mW of active power is now feasible. When factoring in the duty cycle, a GPS receiver estimating a position every 2 seconds will require an average power of 1 mW, which allows a much longer battery life than any of the current designs (Meng, 1997). Table 5-11 shows the Army's progress in reducing the power requirement of GPS receivers.

Research and Development

According to projections by Booz-Allen Hamilton, Inc., there are five major commercial arenas that can be expected to drive the GPS technology base between 1994 and 2003 (NRC, 1995):

- land vehicles (223 million units fielded)
- marine vessels (21 million units fielded)
- aircraft (312,000 units fielded)
- surveying/mapping (690,000 units fielded)
- personal use

GPS market forces are dominated by land vehicles, marine vessels, surveying and mapping, and aircraft. Personal use, including self-surveys, golfing, emergency location, fishing, sailing, and hiking, is expected to be negligible. However, products for personal use are expected to have the same low power consumption and portability characteristics that are needed for the military. The only other commercial market that might potentially need low power would be surveying and mapping. Neither market is large enough to stimulate a major commercial technology push toward Army goals; therefore, low power GPS for the dismounted soldier and other military applications will require R&D investment by the Army.

TABLE 5-11 GPS Power Requirements

Nomenclature	Year	Battery	Power (W)
AN/PSN-8	1985	BA 5590/U	46.5
AN/PSN-9	1987	BA 6598/U	9.8
AN/PSN-10	1988	BA 5800/U 2 each BA 3058/U 8 each	5.0
AN/PSN-11	1993	BA 5800/U 2 each BA 3058/U 8 each	5.0
Land Warrior	2000	—	1.5

Wireless Communication Interfaces

Communications among the weapon, vest, and helmet in the objective Land Warrior system will be accomplished with two RS-232 cable data links connecting the vest computer with the ISM. The ISM can support two displays. One is an actual display in the eyepiece on the ISM located on the weapon. The other is a video output, RS170/RS422, from the ISM either to the vest computer or directly to a display in the IHAS. Normally the ISM feeds the computer, which feeds the IHAS.

Replacing the cables with a wireless interface would have advantages of lower weight and more flexibility. Adopting a wireless interface, however, means using separate batteries for each of the three sensor suite subsystems in the vest, the weapon, and the helmet. Of the three subsystems, the helmet will require the smallest, lightest battery in order to minimize torque on the head from the weight of sensor electronics. This also means that the size and shape of the electronics package must be ergonomically sound. The vest-mounted electronics, because they hang directly from the torso close to the body's center of gravity, have the fewest restrictions on size and weight.

Current and Future Technology

There are two possible approaches to using wireless connectors. One is to rely on radio frequency transmission between the three separate subsystems. The other is to develop infrared frequency transmission (using either LEDs or diode lasers) that use fiber collector nets to complete the link through a variety of different orientations of the subsystems with respect to each other. The latter approach could take advantage of the light collection technology developed to enhance the laser detector (described earlier).

Radio Frequency Wireless Interface The Land Warrior system uses an RS-232 bus for a hard-wire interface. In the RS-232 protocols, all nodes are in a continuous listen/transmit mode, whether data is being transmitted or not. An alternative, more energy-efficient protocol would help to reduce the load on the battery. For example, a DARPA supported program for a wireless interface called a BodyLAN (local area network) uses a time division multiple access (TDMA) protocol at a 900 MHz carrier frequency to reduce power. Other features of the BodyLAN are as follows:

- wireless nodes that can be clipped anywhere on the body
- reliable network range of 1.5 meter, i.e., limited to the immediate proximity of the body
- TDMA timing structure with nodes powered on to receive control information and/or data
- nodes that are provided regular transmission opportunities by the controlling hub and otherwise power-down the transmitters
- varying levels of communications reliability layered on top of the basic structure, ranging from unchecked datagrams to a highly reliable forward-error-correction scheme coupled with packet retries

The anticipated performance characteristics of a BodyLAN system following this set of protocol rules are shown in Table 5-12.

Optical Wireless Interface Once optical wireless links are available at comparable energy consumption levels to those achievable with BodyLAN, one can begin to trade off the advantages of optical and radio frequency links. The chief reason for considering optical interfaces is that they are intrinsically wideband and can thus easily accommodate a more complex sensor suite. Optical links are also highly resistant to jamming.

Trade-offs between low signature, reliability, ease of maintenance, and other criteria, will have to be carefully considered when weighing the merits of designs employing these two wireless technologies, but it will not be necessary to choose one or the other. Optimal performance can probably be achieved by including both a radio frequency and an optical wireless link in the sensor suite. This dual-string design would permit operation in either a normal mode or a clandestine antijam mode, as needed.

The power requirement for a wireless configuration will never be as good as what can be achieved with a well designed hard-wire link. Still, a wireless link should be more reliable because hard-wire connector joints are subject to severe stress in the field.

TABLE 5-12 Performance Characteristics of the BodyLAN

Specification	Near Term	Future
Size	≤ 1.6 in^3	≤ 0.56 in^3
Weight	≤ 15 g	≤ 5 g
Aggregate raw data rate	70 kbps	70 kbps
Power required (full rate)	7.6 mW	5 mW
Power required (sleep)	1.3 mW	0.03 mW
Peak transmit power	375 μm	375 μm
Number of nodes	128	128

FINDINGS

Advancing microelectronics technologies hold great promise for reducing the power requirements of systems for the dismounted soldier. Processing capability and device complexity are growing according to Moore's law, i.e., doubling every 18 months. Processor clock frequency has also risen at a rate of about a factor of ten every nine years. These improvements have brought into focus the importance of energy considerations, especially for portable devices. The performance of portable devices is subject to the limitations of battery technology, which is improving comparatively slowly, despite many years of generous spending on R&D. Both the Army and commercial industry are seeking more energy-efficient systems. Fortunately, they are achievable in most of the relevant technologies.

Communications

The energy efficiency of radio frequency wireless transmission is not likely to improve substantially in the future. However, network architectures and communications protocols can be optimized for energy efficiency. Careful attention to circuit design and operation, system architecture, and system integration have reduced the power requirements of some specialized commercial microprocessors (such as those in cellular telephones) by about an order of magnitude in the past few years. Continued improvement can be expected.

The energy needed to support transmission of high speed data will increase in relation to other Land Warrior energy demands. A tenet of communications systems for the dismounted soldier should be to deploy the computational components of the system in a manner that minimizes wireless communication. In general, computational components should be placed so that data collection and reduction are performed as close as possible to the site of the data collector.

Computing

The Land Warrior computer, basically a general-purpose laptop PC, is connected to all subsystems and is expected to consume about 180 Wh for a 12-hour mission. This demand could be reduced by 50 to 80 percent through system-level power management techniques using general-purpose components and energy-efficient software (compilers that explicitly consider energy per operation). Replacing the general-purpose computer with distributed dedicated processors optimized for low energy consumption could yield reductions of two orders of magnitude. Critical chips within a multimedia terminal combining both computing and radio functions have already been designed to draw 5 mW—three orders of magnitude less than existing commercial counterparts.

Displays and Sensors

Improvements in the drive electronics for both displays and imaging sensors will account for most of the reductions in power requirements for the sensors, the ISM, the IHAS, and the hand-held displays. Digital control electronics of the sensors can be expected to follow the same trends as other computing devices through the use of lower voltage CMOS technology. The exceptions that will not benefit from this steep falloff are the analog subassemblies in the sensor system (i.e., displays, temperature controllers, pulsed lasers, infrared pointers, etc.). R&D already under way can be expected to reduce the power requirements of the combined display and sensor suite to less than 390 mW, more than an order of magnitude better than estimates in the Land Warrior system design.

6

Networks, Protocols, and Operations

Network architecture, communications and computing protocols, and operational doctrine will set major constraints on the power requirements of future soldier systems and the digitized battlefield. This chapter addresses those constraints and considers technological approaches for reducing power requirements for future battlefield networks, protocols, and operations.

Extending wireless communications to individual soldiers will increase the soldier's effectiveness dramatically. Wireless communications account for a major share of the energy used in the Land Warrior system and are likely to dominate power requirements in the future (see Chapter 5). Fundamental limitations, such as the minimum energy needed to transmit a bit of information over a required distance, will place difficult constraints on reducing power for wireless communications. Soldier communications will include access to databases, transfer of images and, very likely, video displays. Some of the technology areas under investigation for the future battlefield include personal communications systems (PCS), satellite-based communications systems, and direct broadcast systems. The Army intends to make maximum use of COTS (commercial off-the-shelf) technology to capitalize on the large market and evolutionary trends in the commercial sector (Leiner et al., 1996). Table 6-1 lists types of wireless communications and required transmission rates (Rapeli, 1995). Clearly, video displays and image-intensive access to databases will place the greatest demands on transmission rates and power.

Commercial technology often advances more rapidly than equipment designed for military use partly because the huge volumes of commercial markets can defray R&D costs (Sass and Gorr, 1995). Commercial wireless communications and personal computers are cases in point. Military adaptations of commercial cellular and PCS technologies could reduce power requirements for the dismounted soldier and enable the Army to keep pace with commercial technology more economically.

Several large scale commercial satellite-based PCS networks will be available for consideration as military assets in the next few years that could support widespread operations by dismounted soldiers with limited power sources. Direct broadcast satellite (DBS) systems should use protocols consistent with low power soldier system operation. The Army could leverage emerging commercial capabilities, such as Direct-PC, a commercial satellite system that provides unidirectional data communications at rates of several hundred kilobits/second to users with small (about 2 foot diameter) antenna terminals. The Army is also considering "pseudo-satellite" repeater concepts using unmanned aerial vehicles (UAVs). But their economical introduction will depend on synergy with developing applications for military reconnaissance.

TABLE 6-1 Required Transmission Rates

Traffic	Required Throughput (kbps)
Speech	8–32
Short messages	1.2–9.6
Electronic mail	1.2–64
Remote control	1.2–9.6
Video	64–384
Database access	2.4–768

WIRELESS TRANSMISSION TECHNIQUES AND LIMITATIONS

The wireless channel that provides communications among soldiers on the battlefield will nearly always be operating in a hostile environment. Communication must be established in the presence of hills, buildings, and foliage, and interference from both hostile and friendly sources will add to the difficulty. Many techniques can be used to make the best of this environment and maximize the ability to communicate reliably. These techniques apply both to the design of individual radio links and to the design of network architectures and methods of sharing the same frequency spectrum (Pottie, 1995). The wireless channel is subject to wide variations in quality as users move (even a few inches) and as other users communicate over the shared spectrum. Mitigation techniques involve either averaging over these variations or attempting to avoid them. Error correction coding, time interleaving, and direct-sequence code division multiple access (CDMA) are examples of averaging over interference and channel variations. Dynamic channel allocation and dynamic power allocation are examples of techniques for avoiding interference. All of these approaches could be used for wireless networks on the battlefield.

Most techniques that increase the capacity of the wireless channel do so at the expense of computational or hardware complexity. Incorporation of these techniques will significantly increase the overall capacity of the network (that is, the overall amount of information that can be transmitted among many potentially interfering users). However, there are fundamental limits on the minimum amount of energy required to send a given amount of information between two points. The remainder of this section discusses these limits.

The energy requirements of the RF (radio frequency) portion of a radio communications system will not follow the rapid downward trend that characterizes the energy requirements of the silicon devices and architectures discussed in Chapter 4. Bounds on DC-to-RF conversion efficiency and information channel capacity are discussed by Forney et al., (1984).

The overall DC-to-RF conversion efficiency of commercial cellular and PCS handsets is between 10 and 20 percent. Improvements in RF transistors may raise this to 50 percent in five to ten years, but the fundamental limit of 100 percent conversion efficiency is immutable. Thus, a realistic upper bound on the achievable transmitter efficiency is at most a factor of four over current technology (perhaps 60 percent overall).

The required signal-to-noise ratio (SNR) for simple modulation/demodulation techniques, such as quadrature phase-shift keying (QPSK) with coherent demodulation (i.e., tracking the received signal phase, the most robust demodulation method) is around 10 dB, for an error rate of about 10^{-2}. With advanced error correction techniques, such as trellis coding, turbo codes, or low rate convolutional coding, a similar error rate for an SNR of around 6 dB can be achieved. These SNR values are realistic minima for acceptable performance because the error rate increases very rapidly as SNR decreases.

The Shannon bound on E_b/N_o (the ratio of energy per information bit to noise spectral density, which is very close in magnitude to SNR) is -1.6 dB; that is, a zero error rate is impossible for SNR values below around -1.6 dB. The difference between the simple technology of today and the almost infinitely complex technology is then only around 10 dB. Practically speaking, even the extremely complex signal processing that will be available in 2015 will probably not permit SNRs below 1 or 2 dB for useful error rates; thus, energy requirements will be reduced, at most, by a factor of five. Together with the previous factor of four increase in transmitter efficiency, the achievable energy efficiency of state of the art wireless information transmission will increase, at most, by a factor of 20 in the future.

Nevertheless, highly advanced digital signal processing techniques will significantly improve the performance of wireless communications systems. Many of today's systems (cellular and PCS systems, for instance) are severely limited by interference. In other words, the noise level at the receiver rises above the inherent thermal noise floor because of interference from other cochannel users. Advanced signal processing techniques, such as multi-user detection and interference cancellation, may significantly reduce this kind of interference. They cannot reduce the underlying thermal noise floor, however, they can ameliorate the increasing levels of self-interference as the existing spectrum is used more intensively. These techniques will also be effective in battlefield applications where intentional jamming can contribute to the overall interference level.

Adaptive arrays are also useful for minimizing the effect of cochannel interference or intentional jamming and enhancing collection of the arriving signal.

Adaptive arrays are useful only at higher frequencies (above 1 GHz), where electromagnetic wavelengths are short enough to permit several antenna elements to fit within the size constraints of soldier-carried equipment. Advances in low-noise receiver front-end amplifiers can make modest improvements in the overall receiver noise floor, but manmade noise in the high frequency (HF, 3 to 30 MHz) and very high frequency (VHF, 30 to 300 MHz) bands, the frequencies used for military communications, and thermal noise from the warm earth will limit these improvements to only a few dB.

Losses in the radio propagation environment will impose fundamental limits on the energy needed to communicate a message. The necessarily low and small antennas available to the dismounted soldier will contribute to these losses. Small antennas are more inefficient at lower frequencies (below around 100 MHz). Shadowing by buildings, trees, and terrain at high frequencies and cancellation from ground reflections at lower frequencies will also create significant problems. At higher frequencies (above 1 GHz), adaptive arrays promise to maximize the amount of signal collected at the soldier receiver.

The characteristics of the propagation environment will limit improvements and determine the amount of signal processing needed to attain these improvements. At the present time, the interaction between antenna and medium characteristics is not well understood, and research in this area may lead to significant gains in overall energy efficiency. The power to maintain a 16-kilobit-per-second (kbs) link can be computed as a function of frequency using available propagation models (Tables 6-2 and 6-3). Table 6-2 shows results for a frequency of 75 MHz (Federal Communications Commission, 1964). Table 6-3 shows similar results for a frequency of 1.5 GHz (Devasirvatham et al., 1993). The tables assume that there is no jamming signal interference.

TABLE 6-2 Transmitter Power Needed to Maintain 16-Kilobit-Per-Second Link at 75 MHz

Communication Distance (km)	Antenna Height (m)	Required Transmitter Power (W)	Required Energy (Wh/Mb)
1.5	1	0.6	0.010
1.5	5	0.025	0.00043
5	1	60	1.04
5	5	2.5	0.04
15	1	6000	104
15	5	250	4.34

Source: Federal Communications Commission, 1964.

TABLE 6-3 Transmitter Power Needed to Maintain 16-Kilobit-Per-Second Link at 1.5 GHz

Communication Distance (km)	Antenna Height (m)	Suburban Residential Environment (inside/outside)		Moderately Treed Environment	
Transmitter Power (W)	Energy (Wh/ Mb)	Transmitter Power (W)	Energy (Wh/ Mb)		
0.5	1	2	0.035	0.0001	0.0000017
0.5	5	0.08	0.0014	0.0000025	0.000000043
1.0	1	50	0.87	0.2	0.0035
1.0	5	2	0.03	0.008	0.00014
5	1	100,000	1700	> 100,000	>1700
5	5	4000	69	> 100,000	> 1700

Source: Devasirvatham et al., 1993.

In both tables a "soldier" antenna height of 1 meter and a required SNR of 10 dB are assumed. At 75 MHz, a noise floor of 10 dB above the room temperature thermal level accounts for manmade noise; an antenna gain of -3 dB (with respect to an isotropic antenna) is assumed. At 1.5 GHz, a noise floor of 3 dB above thermal level is assumed. These tables suggest that higher frequencies may be more appropriate for short distance intrasquad communications, but that the VHF band now used may still be appropriate for intersquad communications. At 1.5 GHz, the significant limitations that manmade obstructions impose on wireless communications are apparent. The figures in Table 6-3 also suggest the potential benefits in terms of energy consumption of multihop system architectures, which are described later in this chapter.

LAND WARRIOR SYSTEM

The Land Warrior system includes radios for communications, a GPS (global positioning system) terminal with navigation capabilities, a computer for processing, a helmet-mounted display, and imaging sensors, such as a thermal weapon sight and a video camera. These subsystems can be broken down into three categories, radios, computing, and imaging. The subsystems are interconnected, with the computer serving as the system core.

Soldier systems for the Army After Next (beyond the year 2025) are likely to require access to satellite-based systems. For example, one-way DBS systems providing links to the battlefield at tens of millions of bits per second (Mbps) could be combined with two-way satellite communications systems to provide tens of kbps for asymmetrical database access. UAV-based technology could also be used if development and deployment of the technology has been completed.

The radio communications network for Land Warrior includes a soldier radio operating in a peer-to-peer network configuration for each soldier. Each squad leader also has a SINCGARS-compatible (single channel ground airborne system) (frequency, waveform, and protocol) radio for communications with other squads and with higher command. The operating power requirement of the soldier radio, while transmitting, is estimated to be 6 W, and the requirement for the squad radio is estimated to be 12 W.

Radio power requirements are dominated by two components. In standby (receive) mode, when the receiver is monitoring for incoming traffic, the power requirements can be as low as 1 W for each radio. The expectation is that these radios will usually be in standby mode, so that standby mode contributes about half of the power requirements during a 12-hour mission. The power requirement increases to 6 W or more during transmission, but transmission is expected to have only about a 20-percent duty cycle, so it also contributes about half of the total requirements. In the near term, voice transmissions will continue to be the predominant form of soldier communications, but data transmissions will become increasingly important as the battlefield is digitized.

Networks, protocols, and operational procedures evolve much more slowly than component technology. For example, protocols for SINCGARS radios (required for the squad radio) originated in the 1960s, and they are expected to be maintained until well beyond 2000. In the meantime, rapid advances in technology have made smaller personal units that readily support faster and more efficient data communication protocols feasible.

The computer includes interfaces to the various subsystems and may be enhanced through software upgrades. Power requirements for the computer are estimated to average as high as 15 W. Voice recognition and control, image processing, and communications are functions of the computer.

The imaging subsystems include an integrated helmet display, a video camera, and a thermal weapons sight. The various subsystems can be placed in standby modes either automatically or manually, so the duty cycle of each subsystem is critical to determining battery life and overall power requirements. The duty cycles are largely determined by network architectures, communications and computing protocols, and operating doctrine.

Power requirements for the soldier system may be dominated by power for the listening modes of various subsystems. Generally, the most direct way to make use of a capability is to operate a subsystem in "hot standby" mode, continuously monitoring for incoming stimuli. This mode supports rapid response and less complex protocols, but it does not support energy conservation. Protocols that activate downstream subsystems when an incoming stimulus is detected can minimize power requirements.

Digital cellular and PCS technologies that are emerging in the commercial market support standby times that range from several days to several weeks, using batteries that store on the order of one to several watt hours (Wh) of energy. Hand-held PCs are becoming available that can operate for about 24 hours and require only 1 or 2 Wh of energy. Rapid advances in digital technology account for most of these large gains in energy efficiency, but advances in protocols also account for significant improvements in energy conservation.

NETWORKS AND PROTOCOLS

Cellular and PCS radio networks are organized in a hierarchical structure, in which terminals communicate with base stations through switching centers but not directly with other terminals (Figure 6-1). These networks are based on call setup procedures and protocols, and the concept of a communications session is fundamental to their design. A base station typically includes more processors, RF circuitry, antennas, and consequent energy demand than the terminals, so the hierarchical structure works to reduce the power requirements of the terminal equipment.

Figure 6-2 shows a peer-to-peer network, which is representative of the radio communications networks for Land Warrior. Terminals communicate directly with other terminals, and no base stations or fixed infrastructure are required. This arrangement is not vulnerable to the loss of supporting infrastructure, but it tends to place larger power burdens on individual terminals than a hierarchical network.

The alerting protocol used in first-generation analog advanced mobile phone system (AMPS) cellular radio systems (for which there are about 40 million terminals in the United States) is a simple procedure. A terminal is placed

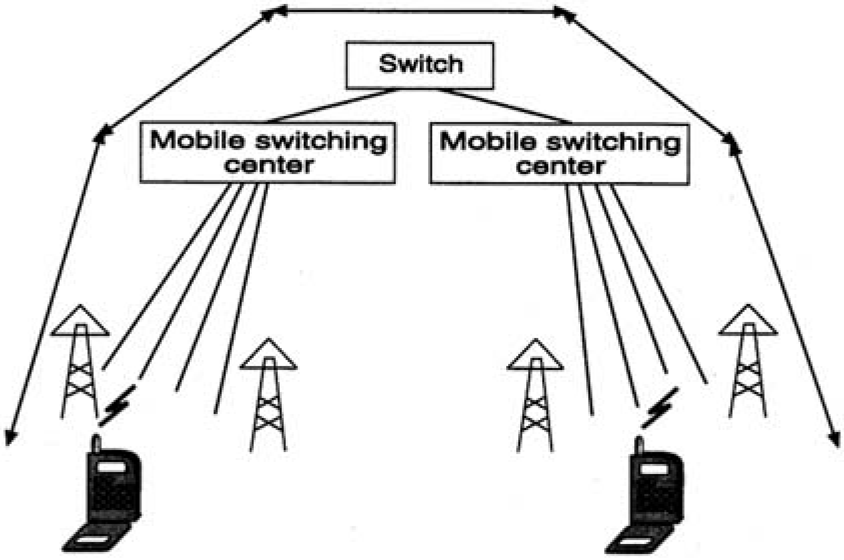


FIGURE 6-1 Hierarchical wireless system architecture used by commercial PCSs and cellular systems.

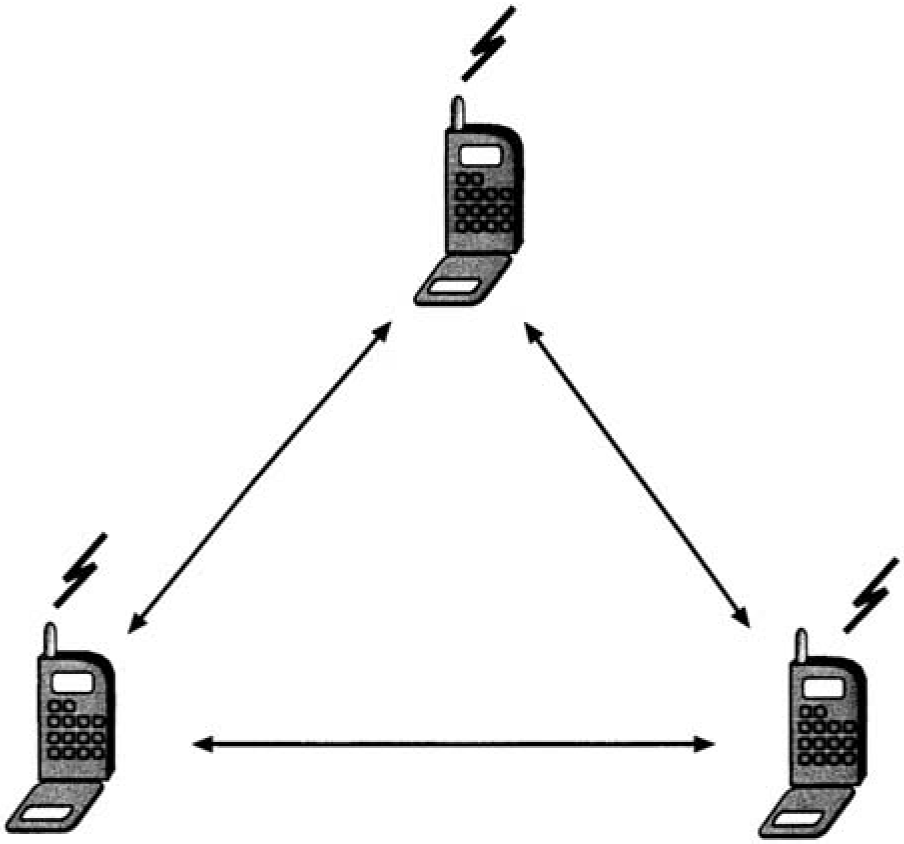


FIGURE 6-2 Peer-to-peer (nonhierarchical) wireless system architecture representative of Land Warrior.

in a continuous receive mode on an alerting channel, where it continuously monitors an alerting stream for its identification number. Cellular radio was originally conceived mainly as a service for vehicles, with terminals with access to large batteries and alternators, so that requiring a receiver to be continuously active was considered acceptable. With the development of hand-held cellular terminals that weigh only a few ounces, however, this protocol design became a major limitation. Hand-held terminals typically provide 8 to 24 hours of standby time, but many users want standby times of days or even weeks.

The protocol used by early paging systems provided for longer battery life than analog cellular systems. Paging systems were designed from the beginning to support small, pocketable terminals with days or weeks of battery life based on a protocol that did not require the receiver to monitor the channel continuously to extend battery life. Instead, pagers were designed to wake up about every 10 seconds to check for the presence of an RF carrier transmitted from the base station. If a carrier was found, the pager would stay in a listening mode until the carrier was released. Base stations would collect pages, and when enough of them had accumulated (about every minute), the base station would activate its carrier.

No traffic was sent for about 10 seconds until all the pagers woke up, and then the pages were sent. This simple protocol dramatically extended battery life and made early paging systems feasible. One undesirable property, however, was that it introduced substantial latency, or delay.

A more advanced alerting network is shown in Figure 6-3. Variations on this scheme are used by digital cellular and PCS systems as well as modern paging systems. An alerting stream from a base station is organized into a periodic frame structure with a large number of time slots. The system protocol distributes its alerting stream across the time slots, so that an individual terminal need only listen to a single time slot in an entire frame to receive alerting messages intended for it. This protocol can result in dramatic reductions in power consumption with only a modest increase in latency. A major requirement of this approach is that a terminal keep accurate time while powering the receiver down and then waking it back up in time to monitor the next time slot. Given the timing stabilities of even inexpensive quartz oscillators, receiver power requirements were reduced by a factor of 100 or more.

Figure 6-4 illustrates, in simplified form, the protocol used by the SINCGARS radios that will be required for the squad radio and is contemplated for soldier radios. This type of peer-to peer network does not involve call setup protocols, which can take several seconds before a conversation can begin. The

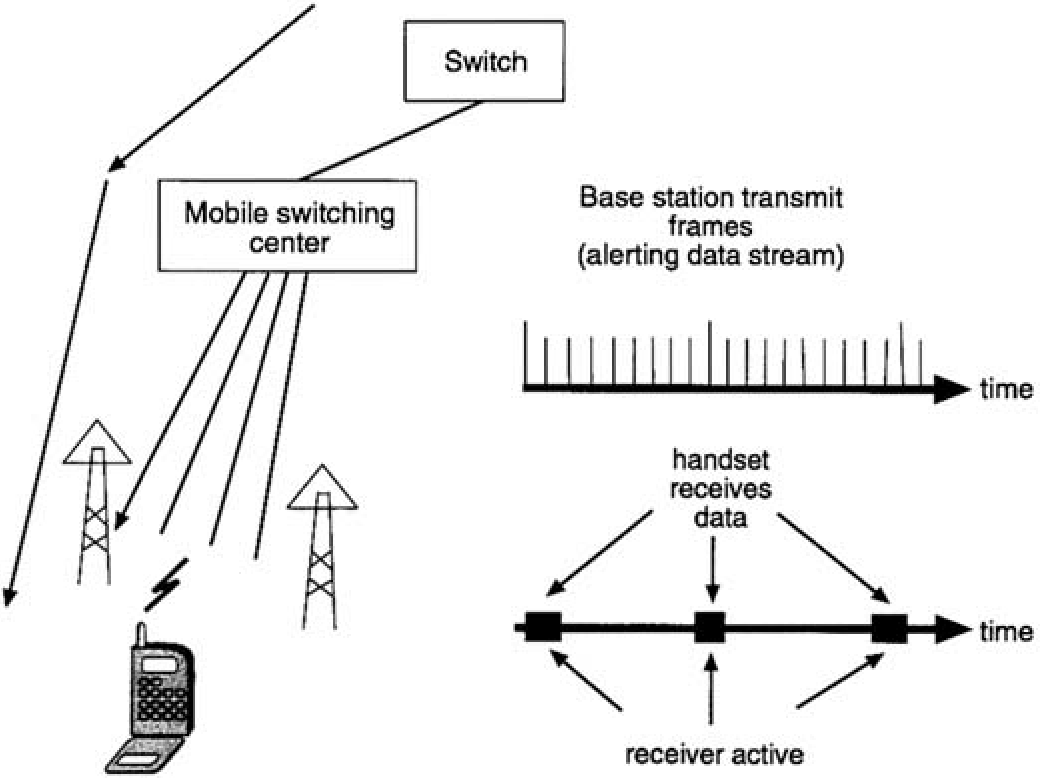


FIGURE 6-3 Time-slotted alerting scheme used by commercial cellular systems, PCSs, and paging systems.

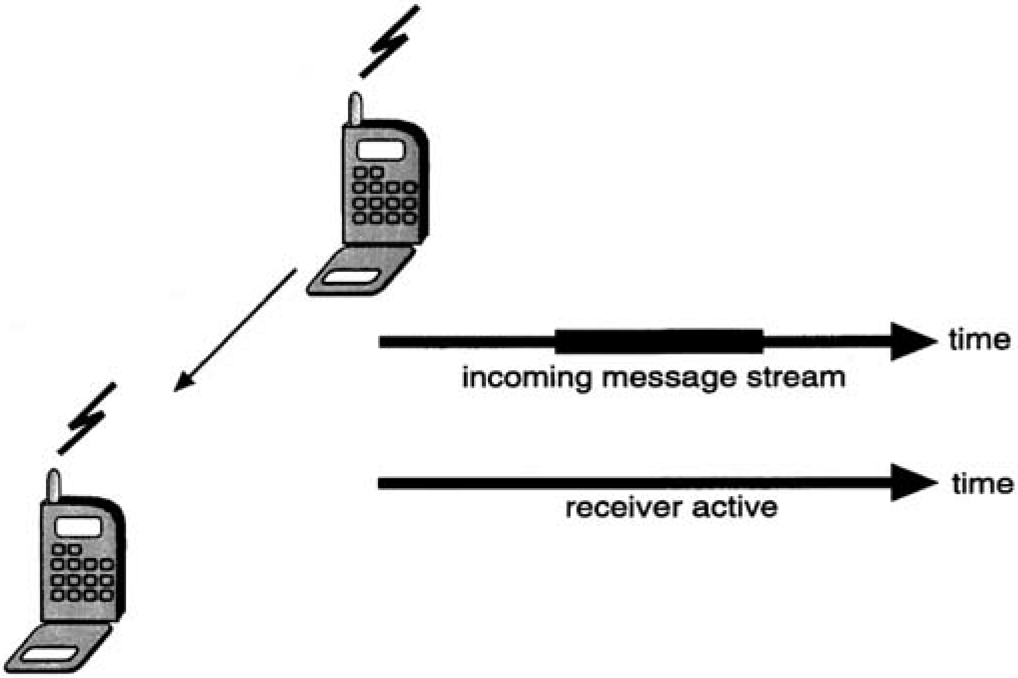


FIGURE 6-4 Simplified push-to talk access protocol used by SINCGARS and other military wireless systems.

protocol more closely resembles a push-to-talk protocol. Since a SINCGARS receiver can be reached by a large number of transmitters and more than one base station alerting channel, and because low latency is desirable, the SINCGARS protocol requires that a radio keep its receiver awake continuously or nearly continuously to monitor for incoming transmissions. This protocol is a major contributor to the power requirements of Land Warrior radios.

The unique needs of battlefield communications—low latency, security, and the ability to continue operating if one or more nodes are destroyed—led to a protocol design based on peer-to-peer carrier-sense networks. However, the protocols for SINCGARS were developed before the widespread use of small personal communicators on the battlefield was feasible. Power requirements of the soldier and squad radios for Land Warrior could be significantly reduced with protocols and network architectures that permit receivers to sleep a large percentage of the time, but the simultaneous requirement for low latency presents a serious problem. Protocols that place larger complexity and power requirements on the transmitter while substantially reducing the complexity and power requirements on the receiver may be possible. Adaptations of commercial digital cellular technologies may also be an attractive alternative.

A project called Personal Communications System for the Soldier proposes to adapt commercial PCS technologies for insertion into the Land Warrior system (Staba, 1996). This program was briefed to members of this committee in December 1996. To date, this project has focused on the insertion of nearly complete technologies and architectures into Land Warrior. As explained earlier, PCS technologies are primarily based on hierarchical networks with fixed base stations and mobile terminals, while the Land Warrior system is planned as primarily a peer-to-peer network. A hybrid network, in which a hierarchical architecture provides "virtual" peer-to-peer capabilities, could reduce the power requirements for wireless communications for future soldier systems and meet the same functional requirements as a true peer-to-peer communications network. Such a network is described in the next section.

Hybrid "Virtual" Peer-to-Peer Network Architecture

Suppose one soldier radio in a squad acted as a mini-base station, repeater, or master radio for a hierarchical network. This arrangement could have several important advantages in terms of power reduction. First, the master radio transmitter could synchronize all other soldier radios, as base stations do in commercial cellular systems, and thereby provide for efficient sleep modes, which would dramatically reduce the power requirement for receivers. This system could offer quick access, equivalent to push-to-talk operation, by waking soldier radios up for only about 1 millisecond every 20 to 100 milliseconds to listen for the beginning of a transmission. The effective duty cycle of the soldier radio receiver could then be as low as 1 percent, if the time to "wake" the radio were less than the 1 millisecond "on" time.

Second, the transmit power could be concentrated at the master radio. A peer-to-peer network in which every station must hear every transmission does not readily support efficient control of transmit power because each signal is transmitted to a number of terminals. With a master radio, each terminal transmits only to the master radio, so power control and reductions in requirements for transmit power can be readily achieved by feedback information from the master radio. The master radio would have to retransmit information to a number of terminals, but its power requirements would be less than for terminals in a peer-to-peer network because it could be located away from the extremes of geographical coverage. Choosing the proper master radio within a peer-to-peer group would minimize that radio's total transmitter energy and the total energy used by the other transmitters in the group. The failure of the master radio and the motion of radios within the group could be accommodated by permitting any soldier radio to serve as the master radio based on an adaptive protocol. If a reliable choice of a master radio within the group was not possible, the network could fall back to operating as a peer-to-peer network. Protocols for configuring and dynamically reconfiguring hybrid networks are not well defined yet and are unique to military communications environments. Research may significantly increase network-wide energy efficiency.

Multihop Network Architectures

In a dense grid of wireless terminals, information that flows between two widely separated terminals may not be needed by terminals lying between the two. Communication may thus be established either directly between the two widely separated terminals, or the intervening terminals may be used as repeaters of the information bound for the distant terminal. Repeaters can reduce the overall energy needed to communicate. To illustrate this, consider the following example. Adding a repeater at the midpoint of a path doubles the number of radio elements involved, but the length of each path is halved. In many scenarios, this reduces the energy needed to communicate a given message by a factor of eight. Because this architecture spreads the energy needed to communicate a message over several radios, energy resources are shared more uniformly by all of the network elements.

The algorithms needed to manage the connectivity in this kind of a multihop network are complex, but they have been the subject of much recent study, especially in the military research community (Leiner et al., 1996). The energy needed to perform the computations must be weighed against the benefits of the multihop architecture. Fortunately, the computational algorithms are subject to efficiency improvements, and the power requirements of the computer platforms will decrease as time goes on. Multihop architectures also offer the benefits of redundant communication paths and the possibility of reconfiguring to replace missing nodes. As long as the underlying radio transmission technologies can still maintain the economic benefits of using COTS technology, a unique military multihop architecture can still be cost effective and energy-efficient.

SELECTING A SUITABLE COMMERCIAL TECHNOLOGY

The next question is how commercial PCS technologies can be adapted for a hybrid network (to provide virtual peer-to-peer capabilities) because all commercial technologies use fixed hierarchical architectures. Table 6-4 lists the seven PCS technologies that have been standardized for use in the United States (Cook, 1994).

Global system for mobile (GSM) communications, a digital wireless technology developed in Europe, is the most advanced PCS technology in terms of commercial development, international acceptance, and subscriber penetration. In fact, GSM is expected to reach a subscriber penetration level of about 200 million in the year 2000. GSM is deployed throughout Europe and most of Asia, including India and China, and it will be widely deployed in the United States. In addition to its frequency hopping capability, GSM (and all other digital PCS technologies) incorporate commercial bit-level encryption technology. This system should permit easy substitution of the more powerful encryption technology required for battlefield applications. Plans are already under way for continued evolution of the technology (IEEE, 1995). Thus GSM should be considered a strong candidate for adaptation to soldier systems.

TABLE 6-4 PCS Technologies Used in the United States

Standard	Tier[a]	Access Method	Number of Users Worldwide (1996)
Omnipoint	low	TDMA/CDMA/TDD	none
IS-95	high	CDMA/FDD	1 million
PACS	low	TDMA/FDD	none (5 million PHS)
IS-54	high	TDMA/FDD	5 million
DCS or GSM	high	TDMA/FDD	25 million
DCT or DECT	low	TDMA/TDD	5 million
Wide-CDMA	high	CDMA/FDD	none

[a] "Low tier" refers to low power or digital cordless telephone technologies with ranges generally limited to 1,000 to 2,000 feet. "High tier" refers to conventional macrocellular technologies.

IS-95 code division multiple access (CDMA) technology is also expected to be widely deployed in the United States. IS-95 uses direct-sequence spread spectrum and should provide low probability of intercept (LPI), low probability of detection (LPD), and anti-jamming capabilities. However, it is highly dependent upon a centralized hierarchical structure and cannot be readily adapted to a hybrid network or to a peer-to-peer network. For example, the forward (base-to-mobile) links and reverse (mobile-to-base) links are very different from each other and use different coding and multiple-access protocols, so terminal-to-terminal communications would be very difficult to arrange.

IS-95 is intended to operate in a frequency division duplex (FDD) mode with continuous activity on both the forward and reverse links, which operate on a pair of frequencies. It is not possible to modify IS-95 for single frequency operation using time division duplexing (TDD) without making extensive changes. The difficulty in obtaining frequencies for use in military operations would interfere with the simultaneous access to paired frequency bands necessary for FDD operation.

Finally, IS-95 will not readily support uncoordinated access of many different channels in a common area. Because all CDMA users interfere with one another, a user near a given receiver would cause unacceptable interference to transmissions from a user farther away (the "near-far" problem). The near-far CDMA problem with IS-95 is managed by centralized feedback power control of the mobile transmitters and by soft handoffs between base stations, which must be executed when terminals cross boundaries between the coverage areas of adjacent base stations to prevent loss of access. Soft handoffs allow terminals to communicate simultaneously with more than one base station when the transmission conditions to the base stations are comparable (e.g., near the boundaries of coverage areas).

"Low-tier" technologies are intended for short-range communications and will not meet the range requirements of soldier radios that must provide communication over distances up to 1.5 km from low "soldier-mounted" antennas. IS-54 TDMA (time division multiple access) technology has a great deal in common with analog AMPS and, therefore, has advantages for commercial deployment in the United States. However, it requires operation with a continuous downlink, which would be a problem in peer-to-peer operation and in single-frequency TDD operation (use of a common frequency for both transmission directions).

The personal handy-phone system (PHS), which is substantially like personal access communications systems (PACS), is now widely deployed in Japan. PHS is a low-tier technology, and thus it is not appropriate as it stands for a soldier radio system. Existing equipment supports operating in both hierarchical and peer-to-peer modes, however, so it is instructive for soldier radio systems. PHS is based on a TDMA approach with eight time-slots in each 5 millisecond frame. Because PHS also uses TDD, protocols could be implemented that support both peer-to-peer and hierarchical access. A variant of PACS technology, the PACS unlicensed B version (PACS-UB), has been optimized for TDD operation in the unlicensed PCS spectrum. Although PACS-UB does not meet the range requirement of the soldier system, elements of this technology are also instructive.

GSM is also based on TDMA (with eight time slots every 4.615 msec) and uses FDD operation. Because the forward link and reverse link for GSM are the same at the physical layer (identical radio channel bit rates, modulation and coding methods, information frame structure, etc.), and because GSM is based on TDMA, it should be possible to adapt it to TDD operation, which is more attractive than FDD for peer-to-peer or hybrid operation. The GSM standard supports frequency hopping, so it should be possible to include frequency hopping in any adaptation of GSM for soldier systems to improve LPI and LPD performance.

Significant reductions in power for soldier systems are possible by designing protocols to support a hybrid network based on an adaptation of commercial technology. The availability of highly optimized components for wireless terminals from the commercial sector, which will accelerate in coming years, should help to reduce power requirements. Hybrid networks should make sleep modes more efficient, thereby reducing receiver power. They should also reduce transmitter power requirements in many cases.

NETWORK ARCHITECTURES ABOVE THE SOLDIER LEVEL

The radio communication requirements above the soldier level (the master radio in the architecture described in the previous section) could become even more energy-hungry. The master, or squad, radio is the gateway to the higher levels of the communications network. Because it collects information from multiple soldier radios, its total information flow may be higher than the soldier radio. Furthermore, the longer and more hostile propagation path to the next level in the network requires that even more energy be expended to send a given message. Because of this, a significant amount of information filtering should be done at the squad leader level. This process may require significant amounts of computational power, but the additional power would probably be more than offset by the reduction in the amount of data to be transmitted. Because the power requirements for computing are expected to drop more rapidly than for wireless communications, this trade-off will become more attractive as time goes by and as the volume of necessary information increases.

The SINCGARS radio protocols will clearly be incapable of meeting future communications needs above the squad level; their capacities are already stressed by existing needs for voice communication. However, the SINCGARS technology will be widely deployed for at least 10 years. During that time, the power requirements for software-defined multimode radios (such as Speak Easy) are expected to fall far below their present 1-kW level. This suggests that software-defined radios at the squad level (or, more realistically, initially at higher levels in the network hierarchy) could provide backward compatibility for gracefully phasing out the SINCGARS technology.

The broad range of communication requirements may be seen to form loose clusters (see Table 6-1). One higher-rate cluster encompasses transferring images, video streams, and large databases. At the other extreme is the lower-rate transfer of short messages, voice messages, and requests for access to databases. This division suggests that separate wireless technologies could be used to meet these two needs. It also offers the possibility of a "fail-soft" mode and more redundancy, in which "basic" communications are carried out on a lower bandwidth technology and high-rate needs are met through another technology. "Slant-path" communications to satellites or UAVs appears to be one way of keeping the power requirements of the high-rate technology within reason. These systems and architectures are discussed in the next section.

NONTERRESTRIAL SYSTEMS AND ARCHITECTURES

Mobile Satellite Systems

Several commercial satellite systems are being planned and deployed to serve mobile voice and low-rate data users in areas of the world where there is no terrestrial infrastructure. The satellite orbits used by these systems range from low earth orbit (LEO) to geosynchronous orbit (GSO). One system architecture, Iridium, uses 66 low-orbit satellites with 2 GHz links to mobile users, 20 GHz links from the satellites to terrestrial gateways, and 60 GHz links between satellites. The satellites form a mesh capable of routing information from one mobile user to any other mobile user or to a terrestrial gateway. Other GSO system architectures cover large areas without intersatellite links. Hand-held subscriber radios typically use transmitter powers of several watts. Coverage is available outdoors in areas with moderate foliage and, often, in the top floor of most wooden buildings. Several of these GSO systems are scheduled for deployment before the year 2000.

Limits in satellite energy generation (solar cells) and the amount of available radio spectrum greatly limit the traffic-handling capacity of GSO systems. Therefore, "dual-mode" (dual air-interface) mobile subscriber terminals are being planned to provide both satellite and terrestrial cellular or PCS interfaces. Whenever possible, a connection would be established through the local terrestrial cellular or PCS network. Some satellite-air interfaces (e.g., Iridium) are designed with this commonality in mind. This commonality could be exploited to create COTS-based soldier or squad-level radios with both a GSM-based terrestrial mode, as described above, and a satellite-based mode for immediate low-rate access to a global network infrastructure.

Direct Broadcast Satellite Systems and Architectures

Direct Broadcast Satellite (DBS) systems based on the low cost commercial home video systems with 18-inch antennas have the potential to distribute huge amounts of data throughout a battlefield with bit rates of more than 20 Mbps. For future soldier systems, this technology would have to be adapted in several ways for low power operation. The requirement for 18-inch dishes is obviously a physical problem at the individual soldier level. Options for using much smaller receiver antennas should be examined. These options could include reducing individual RF channel data rates (to around 2 Mbps) or using spot-beam satellite antennas. DBS technology for high-speed broadcasting could also be combined with two-way mobile satellite systems like Iridium to provide an asymmetrical high-speed database capability.

A key element missing from current DBS architectures is wireless upstream transport capability. DBS is just that—a broadcast technology. Other proposed fixed satellite technologies, however, such as Teledesic and SpaceWay, will provide bidirectional connectivity at rates up to 2 Mbps to antennas with apertures in the 12-inch range. Recognizing the need for even smaller antenna sizes, commercial technologies like these could also form the basis of a bidirectional satellite-based wideband network providing connectivity to the squad level.

Unmanned Aerial Vehicle Systems and Architectures

A potential architecture that would capture the benefits of both terrestrial and satellite-based networks would place "base stations" on high-flying unmanned aerial vehicles, which would fly over the area in which wide-area communications are desired. This kind of network might provide even lower power wideband communication than satellite-based architectures because the distances from the terrestrial terminals to the airborne base station would be much smaller. However, this architecture appears to have only military applications. There is not likely to be a commercial technology base to drive down the costs of the UAV and its repeater payload. In addition, unless the airborne repeaters are deployed fairly densely (e.g., on a 10-mile grid) the low elevation angle from the terrestrial terminals at the edges of the coverage limits would lead to high path losses approaching those for terrestrial architectures, thus negating many of the advantages of the UAV architecture. UAV and aerostat technologies are being proposed for military reconnaissance. It might be fruitful to investigate these programs further to determine if their platform technologies are applicable to military communication needs and if the combined volume of the two applications could produce the needed economies of scale.

OPERATIONAL CONSIDERATIONS

One of the most important steps the Army can take to reduce energy use by the dismounted soldier is to develop protocols and software capabilities that address power discipline in an operational context. Notwithstanding advances in micro-electronics and in optimizing energy supply and demand, the problem of power discipline, which the Army must address from the level of the soldier and the organization in which he functions, remains. The committee was unable to find information about any educational or training programs in power conservation.

Software algorithms that allow communications to wake up via a call or some type of initiator are advances that would improve the equipment a soldier carries. The equipment can be designed to manage the allocation of power so as to minimize, in absolute terms, the amount of energy expended. However, the Army must address power discipline from a standpoint of soldier training to make the soldier aware that energy is a limited resource.

The Land Warrior system fits within a larger operational concept involving other command, control, communications, computers, and intelligence (C^4I) systems, all working together to facilitate the dynamic transmission of battlefield information. The soldier will need a filtering capability to pull down particular pieces of information so as not to become a repository for unnecessary data. The Army is implementing a "tactical internet" to provide near-real-time access to information leaders, down to the squad leader.

Possibly the easiest way to save energy is through system partitioning to move power-hungry operations and databases away from soldier-portable devices. A simple innovation, such as using a UAV as a base station, can produce major savings but would probably also require changes in traditional operational procedures and protocols.

In light of the equivalence of data and energy (explained in Chapter 5), the Army must assess its needs for battlefield data to reach a balance between energy sufficiency and combat effectiveness. This aspect of power discipline, based on the principle of energy conservation, can provide a basis for real-time control of energy use in the field as part of dismounted soldier operations.

FINDINGS

Networks, protocols, and operational concepts tend to have long lifetimes so they will have a long-term impact on power requirements. Much of the power requirement for Land Warrior is for subsystems listening for relatively infrequent stimuli. Protocols and networks that support powering up downstream subsystems only when they are needed can minimize power requirements. This concept of "sleep mode" is applicable to both computing systems and wireless systems. Significant gains over present computers and radios are readily attainable.

Peer-to-peer architecture for radio networks and protocols at the soldier level can satisfy the Army's need for low-latency connectivity, and hierarchical architectures can satisfy the Army's power concerns and have the advantages of using COTS technology. A GSM-based hybrid architecture may offer low cost, low energy consumption, and low latency and provide opportunities for covertness through frequency hopping and encryption.

The harsh radio propagation environment and the wide range of communications dictate that energy-efficient wireless networks be optimized closely to specific environments, which means a wide range of radio interfaces will be necessary. Both terrestrial and satellite-based networks can be used for communications to and from dismounted soldiers. Additional relevant findings include the following:

- Hybrid wireless network architectures in which one radio can serve as a repeater for several others and provide "virtual" peer-to-peer communication with a hierarchical architecture are attractive in terms of energy efficiency.
- GSM wireless technology and wireless access protocols can form a basis for a "virtual" peer-to-peer intrasquad network and can capture most of the economic benefits of COTS technology.
- Better understanding of the interaction between the harsh radio propagation environment and antenna and signal processing characteristics could lead to significant gains in energy efficiency for wireless soldier communications systems.
- Multihop wireless networks based on COTS wireless technology offer the benefits of energy efficiency, reliability, and reconfigurability.
- Satellite technologies (such as DBS, Iridium, Teledesic, SpaceWay) can play a role in supporting battlefield communications to and from the squad level. The Iridium PCS system, for example, is designed to work with GSM-based terrestrial networks. All of these systems offer potentially strong COTS product bases. The adaptation of wideband commercial satellite technologies should take into account the military need for even smaller and more mobile antennas.

- Airborne platforms offer a way to reduce energy consumption by extending radio transmit ranges. UAV repeater technology has no obvious commercial market and may not be cost-effective unless military reconnaissance requirements for UAVs increase.
- Soldiers trained to conserve energy can increase combat effectiveness by practicing power discipline.

7

Advanced Concepts

In the future, dismounted soldiers will be deployed in smaller groups, with each soldier capable of controlling a larger area. The greater dispersion of forces will reduce the soldier's vulnerability to detection but will increase the requirements to operate independently and to communicate over long distances. The Land Warrior system will increase situational awareness and allow dismounted soldiers to detect and engage the enemy at distances that can disrupt the tempo of enemy operations. The systems will provide data on positions, targets, and intelligence, as well as the means of bringing both direct and indirect fire on the enemy. A soldier operating outside the range of the enemy, but inside the enemy's decision cycle, will constitute a new capability made possible by advances in computation and communications technologies.

Chapters 3 through 6 showed that the performance of Land Warrior and future dismounted soldier systems (in terms of weight, bulk, and stealth) all depend on the energy efficiency of the equipment and that there is no single solution to achieving energy sufficiency on the battlefield. Chapter 3 showed that R&D can lead to significant improvements in the specific energy (energy per unit mass) of batteries and other power stores. In particular, the specific energy of batteries could be improved by a factor of two or more, whereas fuel cells and other fueled systems could provide improvements of as much as a single order of magnitude (10 times). Chapters 4 through 6 showed, however, that significantly greater improvements will be gained by reducing energy consumption. Systems that incorporate low power electronics technologies, energy conscious design techniques, and suitable network architectures and protocols can cumulatively provide for improvements of several orders of magnitude.

This chapter discusses the advanced concepts involved in achieving energy sufficiency for the dismounted soldier of the future. It explains the fundamental crisis of energy supply, describes the potential for improving energy efficiencies, estimates achievable energy consumption for dismounted soldier systems, and describes the paradigm shifts necessary to resolve the problem.

COMPARING LAND WARRIOR WITH COMMERCIAL TECHNOLOGY

The initial design of the Land Warrior system includes a suite of sensors, displays, weapons, and communications devices integrated by a general-purpose computer. Powered by standard Army batteries, the system as initially fielded in the year 2000 is estimated to weigh 40 lb and require 50 W of power. The target for energy sufficiency, that is, the average operational time that the system can be used without battery replenishment, is 12 hours. Table 7-1 shows the estimated power requirements for functional devices included in the Land Warrior subsystems. The figures are Army estimates of "function operating power" (that is, power requirements during operation) derived from the Operational Requirements Document (TRADOC, 1994a).

Compact Energy Sources

Chapter 3 showed that the most practical portable energy sources for the dismounted soldier are rechargeable lithium batteries and fuel cells for recharging them. The goal for the near term is a rechargeable battery with specific energy approaching 200 Wh/kg (Watt-hour per kilogram) that has a long life and can tolerate overdischarging and undercharging. For a mission requiring less than 200 Wh, the battery can stand alone but might require an electrochemical capacitor for "load leveling" (meeting intermittent requirements for high power). These capacitors will have specific energy on the order of 8 to 10 Wh/kg, with specific powers greater than 5 kW/kg.

The first fueled systems (most likely fuel cells) will serve as squad or platoon charger stations. These devices will have minimal signature across the spectrum and hence have an advantage over other fueled systems (such as reciprocating engines). Both hydrogen proton exchange membrane fuel cells (PEMFC) and direct methanol fuel cells (DMFC) are inherently more efficient than other fueled systems, although others have the advantage of using current logistics fuels. While the Army has been focusing mostly on improving energy sources, the commercial world has also been exploring new technologies and system configurations to reduce power requirements.

Commercial Electronic Systems

The performance of electronic systems is expected to continue to improve exponentially for at least the next three decades (see Chapter 4). At the same time, consumer applications of advanced technologies will drive down the cost and drive up the performance levels of commercial technologies to levels that are nearly inconceivable today. Several segments of the commercial electronics market, especially devices for digital signal processing, are working to improve the energy efficiency of key technologies used in portable products similar to products required by the Land Warrior. The historical data on the energy dissipation of these devices in terms of the power required to execute one MIPS(million instructions per second) (discussed in Chapter 5) were used to projectfuture performance (Figure 7-1).

TABLE 7-1 Estimated Power Requirements for the Land Warrior System

Land Warrior Subsystem	Function Operating Power (W)
Computer/Radio Subsystem	
Computer	14.8
Hand-Held Flat Panel Display	6.4
Soldier Radio	
Receive	1.4
Transmit	6.0
Squad Radio	
Receive	2.0
Transmit	12.0
Global Positioning System	1.5
Video Capture	1.0
Subtotal	45.1
Integrated Helmet Assembly Subsystem (IHAS)	
Laser Detectors	0.6
Helmet-Mounted Display	4.9
Image Intensifier with Integrated Flat Panel Displays	0.1
Subtotal	5.6
Weapon Subsystem	
Laser Rangefinder	0.1
Laser Aiming Light	0.1
Digital Compass	0.4
Thermal Weapon Sight/Close Combat Optic	5.5
Subtotal	6.1
TOTAL	57.0

Figure 7-1 shows that, even with conservative estimates of the rate of improvement in the energy demand of digital logic, CPUs and programmable DSPs will reach performance levels of 10,000 MIPS/W by the year 1999, and as much as 1,000,000 MIPS/W by 2009.[1] Electronic systems based on this enormous computational capability, along with similar gains in communications systems, could revolutionize military weapons and support systems.

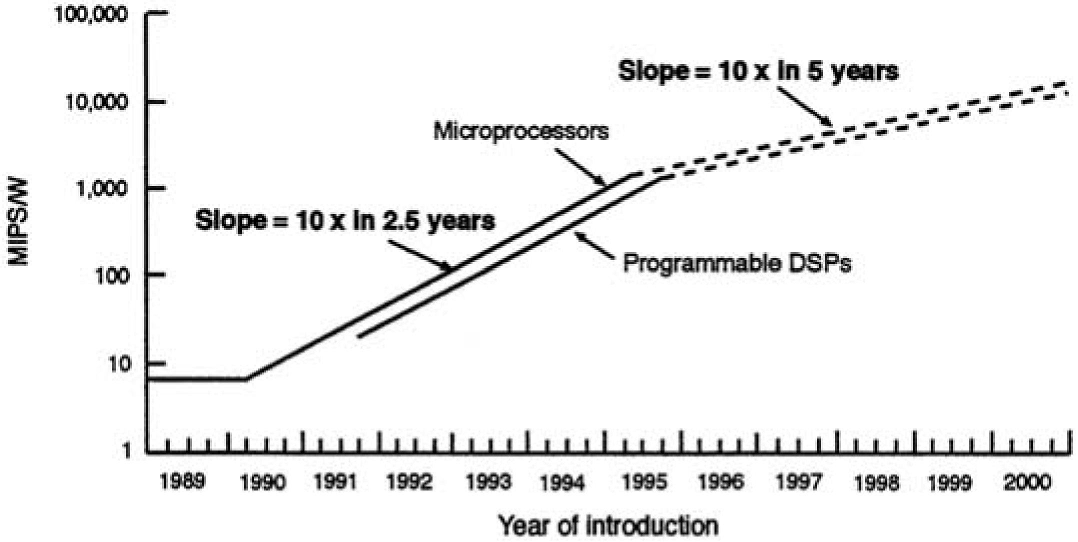


FIGURE 7-1 Projected MIPS/W performance of microprocessors and programmable digital signal processors over time.

In light of these trends, the committee believes that major components of the present Land Warrior design (e.g., the communications/computation subsystem) will be clearly obsolete compared to systems being developed for use in commercial equipment (such as palm-top computers and cellular phones). The rapid rate at which energy consumption is being reduced in electronic systems for commercial markets will produce a growing performance gap between commercial technology and the technology available to the Army through its supplier base.

The committee found that power requirements for Land Warrior had been tabulated rather than optimized and that priorities for using power among the subsystems had not been established. For example, with no priorities for the capabilities that a soldier should carry, the power requirement for the laser red dot is considered as valid as the power requirement for video transmission. Unlike the straightforward requirement for the laser red dot, video transmission has major requirements for bandwidth and compression software to process the video data, which will result in additional power requirements for the system.

Simulations of the trade-offs between electric power and functional capabilities would help the Army quantify the energy costs of the additional electronics and reduce overall power requirements. Only by optimizing both the

---

[1] These estimates do not depend upon the exponential improvements into ultrascale integration forecast by the NTRS and described in Chapter 4. However, if such improvements are realized, even more dramatic reductions in energy consumption for digital computation would be possible.

capabilities of the soldier and the power requirements can the Army expect to field the most capable Land Warrior system.

The Crisis

Chapters 5 and 6 showed that the Land Warrior system will fall short of the vision of the digitized battlefield because of excessive power requirements for computation and radio transmission. The program is on a course to field subsystems that, by and large, are heavier, bulkier, and less functional than comparable systems that could be built using commercial consumer technologies. Over time, as commercial products continue to improve and possess capabilities that the Army is unable to field for itself, a crisis of major proportions will emerge. Even if more energy becomes available, the Army will be unable to use it efficiently to achieve either its current objectives or future objectives for dismounted soldier operations.

This crisis has two components. The first involves the realization of current goals, such as battlefield digitization, and the relationship of these goals to the electrical energy used by the dismounted soldier. Specifically, unless dramatic changes are made in the design of the soldier system and in the associated doctrine, the amount of energy storage required will preclude soldier mobility, even with expected advances in energy source technologies.

Second, unless the Army is able to track and exploit commercial technology in Army-specific designs, potential adversaries will be able to acquire capabilities superior to the Army's from commercial sources. Even more troublesome is that the Army has to do more than catch up with and match commercial technologies. The Army's equipment must have a competitive edge over the equipment of potential adversaries.

USING COMMERCIAL TECHNOLOGY IN THE LAND WARRIOR SYSTEM

In order to quantify the advantages of using energy-optimized designs, the committee developed assumptions and estimated future power requirements based on commercial state of the art technologies. Using the power requirements of the objective Land Warrior system as a starting point, Table 7-2 illustrates the magnitude of the differences between the Army's current power requirements and power requirements that could be achieved using equipment comparable to the commercial equipment expected to be available in 2001. Assuming that the system capabilities remain approximately constant, except for increases in computational capability, the table also includes the committee's very conservative predictions of what should be possible in the year 2015.

In Table 7-2 the committee's estimates for the year 2001 are based on present commercial equipment or on assumptions that the results of current R&D will become available. The projected reductions in power demand in the year

TABLE 7-2 Comparison of Power Requirements for the Land Warrior System and Notional Dismounted Soldier Systems

	Land Warrior in 2001 (W)	Commercial Technology in 2001 (W)	Commercial Technology in 2015 (W)
Computer/Radio Subsystem			
Computer	14.800	0.150	0.010
Hand-Held Flat Panel Display	6.400	0.200	0.007
Soldier Radio			
Receive	1.400	0.100	0.025[a]
Transmit	6.000	1.600	1.520[a]
Squad Radio			
Receive	2.000	—[b]	—[b]
Transmit	12.000	—[b]	—[b]
Global Positioning System	1.500	0.100	0.020
Video Capture	1.000	0.050	0.010
Subtotal	45.100	2.200	1.592
Integrated Helmet Assembly (IHAS Subsystem)			
Laser Detectors	0.600	0.050	0.025
Helmet-Mounted Display	4.900	0.220	0.025
Imager	<0.100	0.050	0.025
Subtotal	5.600	0.320	0.075
Weapon Subsystem			
Laser Rangefinder	0.050	0.050	0.025
Laser Aiming Light	0.075	0.005	0.005
Digital Compass	0.350	0.005	0.002
Thermal Weapon Sight	5.525	1.100	0.160
Subtotal	6.000	1.160	0.192
Wireless Sensor and Display Interconnect	—	0.100	0.050
TOTAL SYSTEM POWER	56.70	3.78	1.91

[a] Power requirements reduced by design improvements.

[b] Power requirements to accommodate range and bandwidth for the squad radio are unbounded; reductions will require improved architecture.

2001 generally involve the Land Warrior program catching up to the commercial sector and thus have relatively low risk in that they will not require breakthroughs or dramatic changes in technology. An implicit assumption, however, is that significant changes can be made in Army requirements and specifications that will allow the use of new technologies. These changes will require a breakthrough in the Land Warrior design and procurement procedures so that subsystems and components with energy efficiency as a primary consideration can be used.

To facilitate the comparison of power requirements in two distinct time frames, the committee used the soldier functions identified for the baseline Land Warrior system in both near-term and far-term projections. This simplifying assumption ignores the very real tendencies for systems to become more complex and for new power requirements to be added that offset improvements. Although predictions of future soldier functions were not included as part of this study, the committee expects that the Army will have to take into account the likely increase in power requirements in its own analyses of future dismounted soldier systems.

Table 7-3 lists the specific assumptions used by the committee in making the projections of technical progress for each of the Land Warrior functions delineated in Table 7-2. Estimates of continued reductions in power for the year 2015 assume that the Army is able to track the exponential improvements in electronics technology that have characterized commercial products over the last 20 years, as documented in Chapter 4. This progress, however, has been based on breakthroughs and technology changes (e.g., the transition to CMOS [complementary metal-oxide semiconductors] from NMOS [n-channel metal-oxide semiconductors]). This will require that the Army be more flexible than ever before. The challenge to the Army is to track these advances and match the rate of improvement of the commercial sector.

The following reasoning was the basis for these extrapolations:

- Power requirements of programmable digital electronics will follow the trend lines in Figure 7-1, yielding a power-to-computation ratio of 0.5 mW/MIPS in the year 2001. To be conservative, the committee assumed that interconnect length and other problems expected to arise in moving to deep submicron technology will increase the ratio by a factor of two to a value of 1 mW/MIPS. The trend curves indicate a further reduction by a factor of 1,000 by the year 2015 to 1 μW/MIPS (a factor of ten for every five years). To be conservative, this figure is also derated by a factor of ten, yielding a ratio of 10 μW/MIPS for 2015.
- Dedicated architecture solutions for digital functions are—again conservatively—a factor of ten (actually more like 100) more energy-efficient than programmable solutions, yielding power-computation ratios of 0.1 mW/MIPS in 2001 and 1 μW/MIPS in 2015.
- Power requirements of the analog circuitry will not improve as rapidly as those of the digital solutions so that a factor of two improvement from 2001 to 2015 is used.
- Transmit power used by the radios is set to 1.5 W, which is approximately the power required to transmit 16 kbits/sec over 2 km at 75 MHz. This is a highly variable quantity and is discussed below.

The operating power levels in Tables 7-1 and 7-2 must be adjusted for estimates of duty cycle and mission time to yield actual battery requirements. However, as can be seen from the numbers in the table, by 2015, if the Army

TABLE 7-3 Assumptions Used to Derive Power Requirements in Table 7-2

Computer
2001 (0.15 W) 150 MIPS computation requirement required for I/O functions, such as speech recognition at 1 μW/MIPS.
2015 (0.01 W) 1,000 MIPS computation requirement at 10 mW/MIPS

Hand-Held Flat Panel Display
2001 (0.2 W) Reflective LCD displays commercially available for "personal digital assistants" require 0.2 W for a monochromatic (640 x 480) display.
2015 (0.007 W) Display technologies allowing refresh rates of 1 frame/sec will reduce power by a factor of 30.

Soldier Radio (receive)
2001 (0.1 W) Includes 30 MIPS of programmable DSP at 1 mW/MIPS, 200 MIPS of dedicated DSP (0.1 mW/MIPS) for security and advanced radio functions, and 50 mW of analog processing such as the power used for commercial cellular radios (e.g., GSM).
2015 (0.025 W) Analog processing will be a factor of two lower than the 2001 requirement and the digital processing will be reduced by a factor of 100 (becoming negligible).

Soldier Radio (transmit)
2001 (1.6 W) Power for the transmit amplifier will require 1.5 W, with the remainder of the functions similar to the 0.1 W requirement for receive functions above.
2015 (1.52 W) Power for the transmit amplifier will still require 1.5 W, with the remainder reduced to 0.025 mW.

Global Positioning System
2001 (0.1 W) 600 MIPS of dedicated DSP (0.1 mW/MIPS), analog processing at 40 mW, based on results of present research.
2015 (0.02 W) Dedicated DSP will be reduced by a factor of 100 to 0.6 mW and analog processing by a factor of two to 20 mW.

Video Capture
2001 (0.05 W) Frame buffers (30 mW) and analog-to-digital (A/D) converters (20 mW) based on low power designs in existing research programs.
2015 (0.01 W) Frame buffer dissipation will be reduced by a factor of 100 (becoming negligible) and A/D conversion by a factor of two to 10 mW.

Laser Detectors
2001 (0.05 W) Sensor uses a technology similar to the technology for active pixel imaging arrays, which require 50 mW.
2015 (0.025 W) Primarily analog functions will be reduced by a factor of two.

Helmet-Mounted Display
2001 (0.22 W) Illumination requires 100 mW for a square inch of display, driver electronics require 20 mW, and the display requires 100 mW.
2015 (0.025 W) Change to virtual retinal displays will allow reduction by factor of ten.
Imager
2001 (0.05 W) Based on research using active pixel sensor.
2015 (0.025 W) Primarily analog functions will be reduced by a factor of two.
Laser Rangefinder
2001 (0.05 W) 50 mW from analog electronics, with negligible power from the 0.75 W laser because of the low duty cycle.
2015 (0.025 W) Primarily analog functions will be reduced by a factor of two.
Laser Aiming Light
2001 (0.005 W) Replacing LED (light emitting diode) with laser allows 1 mW output from 5 mW input.
2015 (0.005 W) Power conversion efficiency of laser will be unchanged.
Digital Compass
2001 (0.005 W) Commercially available.
2015 (0.002 W) Primarily analog functions will be reduced by a factor of two.
Video Camera
2001 (0.5 W) Based on requirements for present video camcorders (450 mW); the imager alone requires 50 mW.
2015 (0.05 W) Replacement of mechanical functions by electronics will reduce power by a factor of ten. Imager alone will be reduced to 5 mW.
Thermal Weapon Sight
2001 (0.6 W) 0.5 W demonstrated for long wavelength sensor and 0.1 W for the heater/cooler.
2015 (0.11 W) Use of thermocouple films (0.1 W), which reduces heater/cooler requirements to 10 mW.
Wireless Sensor and Display Interconnect
2001 (0.1 W) 10 mW/node, 10 nodes.
2015 (0.05 W) Primarily analog functions will be reduced by a factor of two.

---

achieves the same efficiency as commercial technology, either the total mission duration could be increased by a factor of 20 or the required batteries could be reduced by a corresponding amount. When the duty cycle specifications are taken into account, the improvement will be even greater because many of the high power consuming components will have low duty cycles. General considerations for each of the four functional elements in the Land Warrior system, the computer, displays, sensors, and radio communications, are discussed below.

Computer

Table 7-2 shows that the general-purpose computer in the present Land Warrior system accounts for one-third of the energy consumed by the system. The present use of this computer indicates that a conventional laptop is inappropriate to the task. A primary motivation for using a general-purpose computer is backwards software compatibility with DIICOE (the defense information infrastructure common operating environment). Unfortunately, this standard requires the computer to carry 100 million bytes for operating system and application software, and the use scenario requires a duty cycle of nearly 90 percent. This arrangement, with a hard disk drive, is unduly power hungry and is also a single point of failure, which is particularly problematic considering the complexity of the operating system and its reliance on a hard disk drive.

In the short term, a commercial palm-top computer with solid state storage could easily perform all of the functions for which this computer is needed (e.g., storing orders, simple maps), and the sensor processing could be distributed to dedicated processors at the sensor sites. This would eliminate the problem of a single point of failure and improve power efficiency.

In the longer term, a multimedia terminal for the soldier, like the one described in Chapter 5, would be more appropriate. This terminal could be designed primarily as an input/output terminal, with appropriate processing to reduce the external communication bandwidth requirements.

Displays and Sensors

In Chapter 5, the committee developed a prospective suite of displays and sensors and suggested ways to upgrade them into energy-efficient systems for Land Warrior and successor systems. The functions included in the prospective suite are shown in Table 7-2 but are not necessarily the optimal combination for dismounted soldiers. The displays and sensors fall into two classes of energy consuming devices: control electronics and associated interfaces; and application-specific devices.

The control electronics will be able to exploit the reductions in power requirements made possible by commercial advances in electronics technology. The sensors themselves may not realize the same advances, but, as the committee noted in Chapter 5, most of the high energy consumption by these devices in the

Land Warrior system comes from high levels of energy consumption at the analog-to-digital interface. Consequently, the total for the entire display and sensor suite proposed in Table 7-2 is expected to require little more than 300 mW of power by the year 2015. (No power management circuitry is assumed for any device except the laser rangefinder; thus, all devices operate at full power). If, for example, one were to allot a fixed budget of 500 mW for displays and sensors, roughly 200 mW would be available for adding functions, such as a wireless interface, an intercom, a video camera, automation of some sensing functions, or data compression at the sensor chip level. Clearly, the Army would benefit from a concerted effort to improve the energy efficiency of individual displays and sensors so that additional functions could be added without increasing total energy consumption.

Radio Communications

Table 7-2 clearly shows that as power requirements for the subsystems are reduced the percentage of energy required for radio transmissions increases. Although radio transmissions consume less than 15 percent of the power of the objective Land Warrior system (with all systems considered to be on at all times), they could use nearly half of the power in 2001, and more than 80 percent in the year 2015! This problem will be even greater if vastly higher bandwidth requirements and higher transmission frequencies are needed to support the digitized battlefield. In that case, transmit energy consumption requirements will be unrealizable.

Table 6-3 shows that transmitting 16 kbits/sec over a distance of 1 km would require 0.2 W, which would have to increase by a factor of 100 to 20 W to support a 1.6 Mbits/sec video transmission. This problem is so acute in the case of the squad radio, with transmission distances up to 5 km, that the committee did not estimate energy consumption for the squad radio in Table 7-2. The power requirements would be so great as to serve no useful purpose.

The solution to these fundamental communication problems lies in designing a network architecture and the components of this architecture (e.g., use of intermediate repeaters) and using computation-intensive techniques (such as speech and image compression and database caching) to reduce communication needs to a minimum. Even more important, the Army must develop a doctrine that is consistent with the fundamental energy requirements of wireless transmission. This doctrine should recognize the trade-offs between communication modalities (e.g., natural speech, real-time imagery, textual information) and the energy needed for effective communications.

DESIGNING A SYSTEM FOR LOW ENERGY CONSUMPTION

Table 7-2 shows that if the functionality of the Land Warrior system remained constant for the next 20 years, the energy consumption of all Land

Warrior systems, except for the transmit power of the soldier radio, could be improved by a factor of 100. Doing so, however, would require a system design methodology with energy efficiency as a primary consideration like the one now being used for portable consumer electronics.

The Army must develop this kind of a system design methodology if it means to meet the requirements of the future digitized battlefield. However, merely following an energy-efficient system design will not be enough because a new (or possibly even present) doctrine could result in energy requirements that cannot be met at reasonable battery weight levels. The Army must find a way to evaluate the energy implications of doctrine-driven requirements so that planners can provide feedback as a doctrine is being developed. Simulation is one strategy with great potential for energy planning. However, even high level, "back of the envelope" estimates of the power requirements for various levels of communications and computation reveal the critical areas for improvement. The results are presented here in terms of the additional weight of the energy source (e.g., batteries) soldiers will have to carry. This approach also illustrates that energy is just one (of many) resources that can be traded off against other expendables, such as ordnance and food.

For the purposes of calculating energy consumption, the soldier system can be broken down into three basic categories: analog electronics, digital computation, and data transmission. The analog component, which includes the sensors, displays, and analog circuits, such as the front-end of the radio receiver, are best characterized by the amount of time they are operational and their energy consumption during that time. Digital computation is best characterized by the amount of computation, as determined by the number of operations or instructions that are executed, and the energy per operation of the computation architecture. Finally, the energy cost of data transmission is best characterized by the energy required per bit of transmitted data (which, interestingly enough, is independent of the actual power required in the transmission). Each of these categories is discussed in more depth below, with simple equations that can be used to estimate energy requirements.

Energy Requirements for Analog Processing and Analog Devices

The energy source requirements for the sensors, displays, radio receiver, analog portions of GPS, video cameras, laser devices, and imagers can be estimated using the following equation:

$$W_a = P_a \cdot DC \cdot T_m / E_s \quad (1)$$

W_a = the weight in kilograms of batteries that support the analog processing. P_a = the power of the device in Watts (from Table 7-2). DC = the duty cycle, the fraction of mission time a device is active. T_m = the total mission time in hours. E_s = the specific energy of the energy source (Wh/kg).

If the Land Warrior receiver (P_a = 1.4 W) is used 50 percent of the time (DC = 0.5) for a 500 hour mission (T_m = 500) using lithium ion batteries (E_s = 200 Wh/kg), the soldier will be required to carry 1.75 kg of batteries. If the radio power were reduced to commercial levels (P_a = 0.1 W), the battery weight would be reduced to 0.12 kg.

Energy Requirements for Digital Computation

The energy source requirements for the computer and other digital processing can be estimated using the following equation.

$$W_d = (E_{op} \cdot N_{ops}) / (E_s \cdot (3.6 \cdot 10^6)) \quad (2)$$

W_d = the weight in kilograms of batteries that support a given amount of computation. E_{op} = energy per operation (mW/MIPS). N_{ops} = number of operations (in millions). E_s = the specific energy of the energy source (Wh/kg).

E_{op} can be found from the data given in Figure 7-1 for any given point in time. As described in the derivation of Table 7-2, some modifications should be made to take into account future unknowns, such as interconnect limitations and architecture optimization. In Table 7-2, the following values were used:

- For programmable architectures, E_{op} = 1 mW/MIPS in 2001, falling to 0.01 mW/MIPS in 2015.
- For dedicated solutions, E_{op} = 0.1 mW/MIPS in 2001, falling to 0.001 mW/MIPS in 2015. (This probably overestimates the energy required for dedicated solutions, which are often a factor of 100 times lower).

It takes approximately 8 million operations to decompress a single image using standard algorithms. One hour of video would require the decompression of 108,000 images, or 864 billion operations (N_{ops} = 864,000). In 2001, Equation (2) indicates that the soldier would have to carry only 1.2 grams of lithium ion battery to supply the energy for this task.

Energy Requirements for Data Transmission

The energy consumption of a transmitter has three primary components: analog processing (amplifiers, mixers, and oscillators); digital baseband processing; and output power conversion, which includes the energy losses associated with the transmit antenna. Because of the energy efficiency of digital processing, the digital baseband processing for even the most complex modulation will be negligible in comparison to the other components. Therefore, either the analog processing or the transmit amplifier will dominate the energy consumption of the system, depending on the range requirements and the characteristics of the radio environment.

As explained in Chapter 6, by making optimistic assumptions about the radio transmitter efficiencies and radio channel characteristics, a reasonable lower limit for the energy to transmit one bit of information can be found. As shown in Tables 6-2 and 6-3, the required energy varies with the range of the radio link, the radio transmission frequency, and the antenna type and location, all of which are determined by the network and system architecture. For example, using lower radio frequencies requires lower transmission power for the same reliability. This lowers the overall communications capacity, however, which results in either longer times to transmit required information or more co-site frequency interference. Using satellites avoids the high attenuation of ground-based communications, but the increased distance requires larger antennas and higher power transmission. Using UAVs (unmanned aerial vehicles) as airborne relays to avoid the distance problem associated with satellites would be particularly effective because the free space radio propagation characteristics of the path to an airborne station are dramatically better than they are for ground-based transmissions. UAVs could be particularly effective if they were designed with antennas with very large collection areas.

If it is assumed that the energy consumption is dominated by the transmit power, then the following equation can be used to determine the battery requirements:

$$W_c = (E_c \cdot \mathrm{M}) / E_s \quad (3)$$

W_c = the weight in kilograms of batteries to support a given amount of communications. E_c = the energy required to transmit a megabit of data (Wh/Mb). M = the amount of data (Mb). E_s = the specific energy of the energy source (Wh/kg).

At 75 MHz (a standard combat radio frequency), a radio with a 1 meter high, omnidirectional antenna will require an energy expenditure of 0.01 Wh to transmit one megabit of data (E_c = 0.01) over ground for 1.5 km (see Table 6-2). Table 7-4 gives the number of bits to be transmitted assuming different modalities for a standard reporting situation. Thus, 10 seconds of color video requires about 74 Mb of data (M = 74), which according to Equation (3), equates to 0.0037 kg of lithium ion batteries (E_s = 200 Wh/kg). If the distance were increased to 5 km (E_c = 1.0 Wh/Mb), the weight would increase to 0.37 kg.

The higher commercial cellular frequencies of 1.5 GHz would require 0.0034 Wh to transmit a megabit over 1 km of open, moderately wooded terrain (E_c = .0035) (see Table 6-3), thus requiring about 0.0013 kg of batteries to support

10 seconds of video. This battery weight, however, would increase by 250 times to 0.3 kg in a residential (indoor/outdoor) environment (E_c = 0.87 Wh/Mb). Clearly, long distance, high bandwidth transmission should be used sparingly, and a network architecture (such as the one described in Chapter 6) that uses shorter distance transmissions is required. To see the difference, one only has to calculate the requirements for a transmission of 0.5 km at 1.5 GHz over open terrain, an E_c = 0.0000017 Wh/Mb that would probably be dominated by the analog processing in the transmitter instead of the output power.

TABLE 7-4 Number of Bits Required to Transmit a Situation Report by Different Modalities

Modality	Bits to be Transmitted
100 Words	
Text[a]	2,000
Speech[b]	144,000
Still Picture[c]	
Black and white[d]	41,000
Color[e]	246,000
Video[f]	
Black and white[d]	12,300,000
Color[e]	74,000,000

[a] ASCII coding with 2:1 data compression
[b] One minute of digitized audio
[c] Video data is for 30:1 MPEG2 compression
[d] 16-level gray scale
[e] 256-level
[f] Ten seconds of video

Terrestrial wireless communications could be supplemented by satellites in the future. Multisatellite systems, such as the planned Iridium or Teledesic systems, would give soldiers access to a global network (of relatively low bandwidth) that could supplement the higher bandwidth, shorter range soldier's network. Direct broadcast satellite technology could also be adapted to provide two-way communications. Another long-term possibility would be to use a multihop architecture, transmitting information between widely separated terminals via intermediate terminals acting as signal repeaters. Using UAVs to carry repeaters would have the airborne radio propagation characteristics without the distance penalty of satellites. Although the algorithms are complex, they are already being investigated under DARPA sponsorship.

As the examples above and the data in Table 7-2 indicate, communications will set the energy requirements on the future digitized battlefield. Thus, the information architecture can profoundly affect the amount of energy consumed by the dismounted soldier. In the simplest form, a 100-word report in a standard Army format requires fewer than 2,000 bits if it is transmitted as text or 144,000 bits if it is transmitted as digitized speech (Table 7-4). A color still picture can require up to 250,000 bits, and a 10-second color video clip can require up to 74 million bits. Because the amount of information in bits required to report a given situation varies by almost five orders of magnitude, the battlefield information architecture must be coupled with the radio transmission architecture to determine actual energy requirements for the dismounted soldier.

PARADIGM SHIFTS

From the considerations described above, it is clear that the Army will not be able to achieve its vision of providing the soldier with situational awareness entirely and that energy sources alone will not account for all of the limitations on dismounted soldier capabilities. Energy sufficiency through the use of energy-efficient technologies, on the other hand, is achievable from a purely technological standpoint by 2015 and could become reality for the Army After Next.

The committee is not optimistic that the Army will be able to make the necessary fundamental changes to exploit the expanding base of advanced technologies, particularly as communication requirements increase. But unless the Army takes steps to maximize the energy efficiency of portable electronic systems for the dismounted soldier, the performance of these systems will continue to be limited by the available energy sources, and the Army's advantage in battle will be jeopardized. Paradigm shifts in energy philosophy, system design, and the use of commercial technology are needed to change the way military electronic systems are defined, developed, and purchased. Otherwise, the crisis will not be resolved.

Energy Strategy

The Army must focus on energy consuming systems as well as on energy supplying systems. Energy is a vital, depletable resource that must be carefully budgeted and conserved during every aspect of the definition, design, development, and procurement of portable electronics. Energy translates directly into weight, bulk, stealth, and data-handling characteristics, all of which are quantifiable in common terms. Understanding the equivalence of energy and other system measures can allow the Army to be more flexible in defining requirements.

System Design

Energy efficiency must be considered in all phases of system design:

- Equipment development and procurement procedures must set tight energy consumption budgets for all elements of future electronic systems, including hardware, software, and packaging. A philosophy widely used in industry is that all equipment must be designed to achieve target battery life goals. The battery problem will not be solved by inventing better batteries; it will only be solved by rigorous power management design procedures.
- Design procedures must include software. Future systems will have increasing levels of software-defined functionality, and the operation of the software could override power saving features built into the hardware. The perception that software functions are "free" must be changed—every cycle a computer operates to execute a program consumes energy from the energy source. Thus, software must be subjected to the same rigorous power management design procedures that guide hardware development.
- Energy consumption learning curves should be used in the specification, development, and procurement of electronic systems. In other words, the energy consumption budget allocated to specific functions should be changed over time in accordance with industry learning curves. Thus, according to the data in Figure 7-1 and the discussions based on Table 7-2, a programmable DSP system should be specified to operate at no greater than 1 mW/MIPS for systems developed for 2001. The goal should be lowered to 0.01 mW/MIPS for systems developed for 2015. Setting specific goals will motivate contractors to face the trade-offs necessary for developing dedicated architectures.
- Consistent with using learning curves to move toward lower energy consumption, designs should move towards lower operating voltages. This is especially important for digital functions (Chapter 5), and industry is driving digital operating voltages towards the 1 V level. Standard operating voltages can be established for categories of electronic functions, and these voltages can be lowered with time.

Use of Commercial Technology

Army systems must be closely coupled to the technologies used in commercial products. This is the only way to guarantee that the Army can keep pace with and benefit from commercial advances:

- Very large scale ASIC (application-specific integrated circuit) technologies are being used in commercial products to implement low power systems on a chip. Interchip connections consume increasing levels of power as the system clock rate is increased, and chip-scale systems integration will be essential to achieving low power operation in the future. Also, custom integration is frequently the only way low power system operation can be achieved because many low voltage functions are not available as stand-alone components.
- Traditional suppliers of military electronics, even though they may be associated with consumer electronics organizations, are often isolated from the advances in products and technologies that the Army needs for low power, high performance portable electronic systems. In many large companies, military and commercial products are developed, produced, and marketed by different business units with very different goals and objectives. Evidence of this is that a major switch in emphasis to low power electronics as a solution to the battery life problem in consumer electronics began in earnest in the early 1990s (see Chapter 5). Major improvements in the energy efficiency of electronics are now being made in response to commercial market incentives.

8

Research Objectives

This chapter proposes 20 strategic research objectives that are critical to future energy sufficiency on the battlefield. It also highlights particular steps that should be taken to fulfill those objectives. For planning purposes, the chapter provides implementation guidelines based on the committee's assessments of commercial and military activities in the technology areas addressed in this study.

ENERGY SOURCES AND SYSTEMS

In the near term, the Army's pursuit of better energy sources for the dismounted soldier will continue to depend on the development of commercially viable sources with higher specific energy; these energy sources must be safe, rechargeable, lightweight, undetectable, reliable, adaptable to military configurations, and supported by domestic manufacturers. All of these criteria cannot be met with batteries. Therefore, the Army's research should focus on small, lightweight, intermediate-store fueled systems. The committee also believes that research in human-powered systems has the potential to meet the level of autonomy that will be necessary for dismounted soldiers in the Army After Next (after 2015).

Rechargeable Batteries

Improvements on the order of a factor of two or more can be achieved by advances in processing technology, active material composition morphology, reinforcing components, electrolytes, and components with limited cycle life and recharging rates, such as separators. Rechargeable batteries have significant logistic advantages for the Army, but their specific energy is only about half that of equivalent primary batteries. An immediate goal for the Army is to develop a rechargeable battery with specific energy equivalent to the best primary battery, about 200 Wh/kg. Chargers and state-of-charge devices, which are relatively inexpensive, have a major effect on battery performance and safety. The main goal of research in this area should be to incorporate new and improved circuit components as they become available. Advances in charging methods can provide for more rapid recharging, longer cycle life, and higher performance.

Chargers and State-of-Charge Devices

These relatively inexpensive electronic components have a major effect on battery performance and safety. The Army must maintain the option of incorporating improved circuit components as they become available. Advanced charging methods can provide rapid recharging, longer cycle life, and higher performance.

Aqueous Systems

Significant improvements in specific energy, specific power, and cycle life can be achieved by optimizing the structure and particle size of reactant materials. Other areas of investigation of interest to the Army include:

- low cost methods for active material preparation (candidates include xerogel and aerogel methods; nanostructural materials; and optimized heat treatments)
- improved separators for better electrolyte wicking and retention for longer cycle life
- substrates for electrodes that can act as structural materials, current collectors, and bipolar sheets
- seals to prevent leaks, allowing for maintenance-free cells
- advanced electrolyte systems, new compositions, and gelled electrolytes

Lithium Systems

Research areas of interest to the Army for rechargeable lithium cells include:

- overcharge and discharge tolerance via cell design and charge control
- improved positive electrode materials and preparation methods for long cycle life, low cost, and environmental acceptability
- electrolytes with greater stability, improved conductivity (both polymer and liquid), and nonflammability
- management of the Li/electrolyte interface and film
- lower cost separators
- electrochemical couples of higher specific energy

Fuel Cells

Fueled energy sources offer the most potential for meeting the needs of the dismounted soldier. The following are the key research areas:

- more efficient methods of storing and/or generating hydrogen fuel
- reducing operating pressures to near atmospheric pressure
- improving the carbon monoxide tolerance of systems using reformed fuels
- reducing the cost of bipolar plates/flow fields
- reducing system complexity
- improving water management
- reducing the cost of proton exchange membranes
- improving catalysts for direct methanol fuel cells
- reducing the rate of methanol crossover
- increasing specific power to higher than 100 W/kg for small (< 100 W) systems at atmospheric pressure

Advanced Fueled Systems

Advanced fueled systems, including thermophotovoltaic systems, microturbines, and hybrid systems, will enable the revolutionary increases in dismounted soldier combat capabilities for the Army After Next. Of these capabilities, microclimate cooling will continue to be the most demanding (in terms of energy) of all of the capabilities studied by the panel. Successful development of a microclimate energy source will depend on the mission profile, the size of the energy storage unit needed for the mission, and the efficiency with which the stored energy can be converted to active cooling. Continuous high level cooling for missions longer than a few days will clearly require massive energy sources, i.e., high specific energy fueled systems with power levels above 150 W and several kWh of stored energy. Innovative, efficient conversion technologies for converting stored energy to active cooling will also be necessary.

Microturbines

The most revolutionary, and possibly the highest risk, advance proposed for compact power systems based on rotating machinery is for miniaturized turbines driven by combustion or high pressure gases. Key research areas include:

- liquid combustion in small systems
- active noise cancellation
- microturbine fabrication
- miniature electrostatic generators
- thermal signature mitigation

Thermophotovoltaic Systems

The potential for TPV (thermophotovoltaic) power systems has already been demonstrated. The next step is to build prototype systems for evaluation and then focus research on correcting flaws and inadequacies. Several R&D topics must be thoroughly investigated before optimized TPV systems can be developed. The most important are:

- liquid fuel combustion in small systems
- strong robust radiators
- bandgap tailoring in photovoltaic materials and devices
- design of cavity structures, including emitters, filters, cell arrays, and coolant/recuperator schemes
- high temperature recuperators
- prototype systems

The necessary fabrication technology must be established concurrent with these demonstrations and experiments. Research should also focus on characterizing the capability of each component within the framework of the application for the dismounted soldier. The successful application of TPV technology must result in weight savings, cost savings, added capability, and reliability. At the component level, the priorities are:

- demonstration of a diesel burner/recuperator/emitter in an integrated unit
- development of optimized, affordable photovoltaic cells
- development of the optical cavity consisting of emitter, photocell, and filter as an integrated unit

Hybrid Systems

Numerous laboratory demonstrations of hybrid systems that would be applicable to the dismounted soldier have been made. Pulsed power techniques have been extensively employed in the high power regime; however, no field tests have been done to determine the utility of this approach to human-portable power. To optimize the design, it will be necessary to have information on the power demand time history for a variety of mission profiles. Based on this data, a hybrid system could be designed for a worst case scenario that maximizes available energy.

The success of hybrid systems depends on the successful development of each component in the hybrid power train. The key issues are developmental. They include the following:

- development of computer models for predicting hybrid system performance as a function of mission profile

- development of laboratory prototypes
- reliable field data on which to base energy utilization profiles of the various soldier subsystems

Human-Powered Systems

Human-powered systems will become increasingly important as the duration of operations by the dismounted soldier is extended. Converting the energy associated with body motion to electricity would radically improve the dismounted soldier's capabilities. To exploit the potential of human-powered systems, the following research areas should be explored:

- efficient lightweight intermediate storage units
- analysis of the motions involved in routine tasks and coupling unobtrusive converters to this motion
- laboratory prototypes employing small electromechanical and piezoelectric converters

LOW POWER ELECTRONICS AND DESIGN

Technologies in low power electronics and design have benefited greatly from the incentives of the commercial marketplace. Army systems, particularly those on which the future dismounted soldier will depend, have not generally benefited from commercial development. The research objectives described below are particularly relevant to meeting the Army's needs.

Circuit Design Tools for Minimizing Power Requirements

The commercial driving forces behind CAD (computer-aided design) tools for highly complex circuits have been improved circuit packing density, higher performance circuits, self-testing circuit modules, and an improved automated design process. Commercial developments in low power electronics have focused on silicon efficiency (area and performance) but not on reducing energy consumption.

The Army needs new design tools that include energy efficiency as a major goal. These tools should focus on determining the energy used at each stage of the design process and making circuit design and layout decisions that would minimize power requirements. Each parameter that affects power should be considered for each step in the circuit design and implementation, from logic to circuit to device.

Architectural Design Level Tools

At the architectural design level, tools should allow the designer to explore, evaluate, compare, and optimize energy dissipation alternatives early in the design process. At this level, switching activity, the required operating voltage level for each circuit block, and the capacitance of each circuit node should all be considered for their affect on power requirements. Power-down or "sleep" circuits to minimize the standby power required for inactive circuits can also be incorporated at this level. Energy savings can also be obtained by optimizing the instruction set or using a hardware module to implement a specific data path to execute a specific instruction.

Packaging Techniques for Minimizing Interconnects

Significant energy savings can be made by choosing the proper package design for integrated circuit input and output connections. The number of connections should be kept to a minimum to reduce the number of energy-consuming drivers; the capacitance associated with each interconnect node should also be minimized. Although the use of multichip modules will be beneficial, the Army should use packaging techniques with low interconnect capacitance.

Submicron Lithography

The semiconductor industry is committed to achieving the goals of the NTRS (National Technology Roadmap for Semiconductors) and has been making large investments each year in pursuit of those goals. As the apparent fundamental limits are approached, even larger investments in submicron lithography and advanced fabrication techniques that cannot be funded solely through commercial sales will be necessary. For the Army to keep pace with commercial progress in low power semiconductor technology, it must monitor and support advances in technology and be sensitive to industry's limitations.

Optimizing Device Design

At the device level, individual transistor designs can be optimized to reduce the power required. Clever transistor geometry layout can be used, for example, as well as technologies with low leakage currents. Device current ratios and threshold voltages can also be optimized to reduce power. Leakage current can be minimized by using SOI (silicon on insulator) technologies, including silicon on sapphire with thin silicon conducting layers. Research in this area would extend the work supported by DARPA (Defense Advanced Research Projects Agency) on low power circuits on SOI.

Design Methodologies for Army "Systems on a Chip"

By the year 2010, commercial progress in fabrication technology will yield an increase of 100 times more transistors on a single integrated circuit. This advance would permit all of the functions that are planned for the Land Warrior system to be easily implemented on a single chip. In fact, capabilities far beyond Land Warrior's computation and communication capabilities could be implemented, including support for low energy networking, protocols, signal processing, and analog capability for interfacing and processing data from various sensors. Additional computation circuitry to compress data, which would reduce the power required for data transmission, would also be possible. This high level of integration will allow architectures that reduce energy consumption and size.

The Army should support research on customizing design methodologies to reduce total energy consumption. The application of board level design methodology to monolithic chips will be critical. This will mean integrating modules from different suppliers into a single circuit (just as chips from different suppliers are integrated onto the boards used in Army electronic systems today). Standard interfaces for these modules must be defined, as well as methods of testing, technology compatibilities, and methods of verification that are far beyond present day capabilities.

COMMUNICATIONS, COMPUTERS, DISPLAYS, AND SENSORS

In general, the Army must be prepared to embrace commercial electronics technologies that have the potential for improving energy-efficiency by factors of 10 to 50 for a given level of performance. In addition to making progress in microelectronics circuit design, industry is working at the product level to use lower supply voltages and to optimize systems architectures with more parallel processing and more efficient distribution of functions between hardware and software. With ASIC (application-specific integrated circuit) systems-on-a-chip technology, it is possible to customize energy efficient systems even for the relatively small production runs needed for dismounted soldier systems. Key research objectives are described in the following subsections.

Terminal Equipment Architectures for Optimizing Energy Consumption

The Army should capitalize on the DARPA program to develop a low power multimedia terminal (discussed in Chapter 5). This program includes optimizing the communications architecture, processing hardware, and device architecture for a military terminal. The goal is to require only 5 mW of power, even during constant operation. This research merges the communications and computing functions.

Component and Human-Computer Interfaces

Army-sponsored research should focus on developing embedded, dedicated computer systems, rather than adapting general-purpose personal computers. Ideally, each sensor or subsystem should have its own processor and wireless transceiver, and user level programming should be minimized.

Designing human interfaces should be given serious attention because efficiency depends on simplicity and clarity. To minimize the number of human inputs, the soldier's tasks must be modeled and interfaces closely matched to tasks. The range of available input interfaces is growing; within a year or two it will include not only the keyboard and mouse on an iconic desk top, but also voice and handwriting recognition, position sensing, and eyeball tracking. Output options will include speech synthesis and heads-up displays. The processing requirements (and thus the energy consumption) of various output and input methods will vary over several orders of magnitude. Particular research challenges include the following:

- Matching capability with applications. The current thinking is that the highest performance capability is the most desirable. However, this capability is often unnecessary, and enhancements, such as full color graphics, require substantial resources. High performance enhancements may actually decrease ease of use by generating information overload for the user. For example, the Marine Corps Hunter-Warrior field exercise provided forward observers with hand-held personal digital assistants. Almost 60 percent of the messages were position situation reports that required only short textual messages (Seaton, 1997). Systems design should focus on the most effective means of accessing information and resist the temptation to provide extra capabilities simply because they are available.
- Input/output modalities. Modalities that mimic the input/output capabilities of the human brain have been the subject of computer science research for decades, but they are still inaccurate and difficult to use. Many require extensive training, and inaccuracies often frustrate users. In addition, most of these modalities require extensive computing resources that increase energy consumption and weight.
- User interface models. Appropriate metaphors for providing mobile access to information (that is, the next "desk top" or "spreadsheet") typically take more than a decade to develop because they require extensive experimentation and because different applications or information types may require different metaphors.
- Quick methodology for evaluating interfaces. Current approaches to evaluating a human-computer interface require elaborate procedures and scores of subjects. Evaluations may take months, and they cannot be done while the interface is being designed. New methodologies should focus on reducing human errors and frustration.

Ultra Low Power Displays and Sensors

Lower energy consumption by display subassemblies can be achieved by long-term R&D. First, system level design trade-offs should be introduced early in the display development stage. Considering the reduction in energy consumption that can be achieved by eliminating the analog-to-digital conversion step, the necessity for the digital format should be investigated, especially for functional enhancements that are planned downstream. The wide field of view of the virtual retinal displays will mean meeting the mechanical challenges of the scanning function. The human-display interface format must be optimized for maximum situational awareness. Data collection and simulation modeling are also needed.

Further development of MEMS (microelectromechanical systems) technology for microbolometers will improve the performance of uncooled infrared sensors. This will mean higher resolution of the imager and minimizing the temperature extremes over which control must be maintained. The energy efficiency of the sensors and displays could be improved through development of an optical fiber collector net to feed data to a central detector processor. Similar architectures might be used to support electronic sensors for optical energy, radio frequency energy, chemical agents, or radioactivity.

Multimodal and Adaptive Communication Circuits

To achieve the flexibility and energy reductions in radio modem circuits that will be possible in future integrated circuit technology, the Army will require designs that allow analog radio frequency circuitry to coexist on the same circuit as digital processing optimized for low power. This capability is necessary because radio architectures that are mostly digital will make it possible to reconfigure or reprogram the digital portions of the circuit to adapt to different modes of operation. Army radios could therefore use communication system architectures that adapt to the environments in which they are used and to the tasks for which they are being used. For example, a radio system that is energy optimized for voice transmission among members of a squad in a rural environment will be quite different from one that is emulating a commercial protocol to exploit existing infrastructure in an urban setting. It would be highly desirable to have a single portable radio that could be adapted to as low an energy level as possible for various tasks and environments.

Evolution of Hardware and Software

As fabrication technology improves, the energy penalty for implementing a given communications or computation function in a flexible software solution rather than in a dedicated architecture will decrease. To keep from lagging behind the commercial technology, the Army must continually update computation and communication circuits. Updating will require a modular, upgradeable architecture as well as a design methodology that can accommodate the energy trade-offs between dedicated hardware solutions and software implementations. In addition, software compilers and operating systems that minimize energy are needed for the software-enabled parts of these systems, which also must allow more energy-efficient hardware to be used without costly software rewrites.

NETWORKS, PROTOCOLS, AND OPERATIONS

Key research objectives to support the Army's goals for energy-efficient networks, protocols, and operations are described below.

Wireless Battlefield Communications Network

The Army should pursue research aimed at adapting commercial cellular and personal communication system networks and technologies to the needs of future soldier systems. As explained in Chapter 6, radio networks and protocols at the soldier level require peer-to-peer architectures for low latency connectivity and, simultaneously, require hierarchical architectures to meet power concerns and the capability to use COTS (commercial off-the-shelf) technology. The international (hierarchical) GSM (Global System Mobile) standard now offers low cost, low energy consumption, low latency, and is adaptable for covertness and security. A hybrid wireless network architecture that provides "virtual" peer-to-peer communication with a hierarchical physical architecture based on GSM should be adapted and optimized for the dismounted soldier.

Extending the Range of the Dismounted Soldier

The Army's wide range of communications requirements dictates that energy-efficient wireless networks be optimized for specific environments, which will require a wide range of radio interfaces. Terrestrial and satellite-based networks can be part of the overall communications pathway to and from the dismounted soldier. Specific research objectives in this area include:

- creation of dynamic network management protocols for multihop, multiply connected networks
- incorporation of signal processing algorithms to cancel or avoid interference and jamming
- investigation of architectures involving satellite or other aerial repeater platforms

Sensors and Software for Power Management

Much of the power requirement for Land Warrior and successor systems will be attributable to subsystems listening for relatively infrequent stimuli from inputs. Protocols and networks that support powering downstream subsystems only when necessary can reduce power requirements. This "sleep mode" concept is also applicable to computing systems and wireless systems. Automatic or soldier-mediated control of high power functions will conserve energy that can be used to transmit images and video.

Models for Optimizing Energy Efficiency

Energy efficiency directly affects the combat effectiveness of the dismounted soldier by determining the weight, bulk, data-handling capacity, and stealth characteristics of battlefield equipment. Simulation models that incorporate models of soldier effectiveness and behavior will make possible trade-offs among localized computation, distributed databases, information dissemination patterns, and soldier operational doctrine to optimize the design of dismounted soldier systems. Research areas include:

- cost/benefit (energy consumption/combat effectiveness) studies of high rate information flow on the battlefield
- system level simulations that incorporate soldier behaviors and computation/communications trade-offs on the battlefield to evaluate power discipline (both automated and manual) and to optimize overall energy consumption

Propagation Characteristics and Antenna Design

Energy for radio transmission will dominate power requirements for the dismounted soldier of the future. The complex radio propagation environment is heavily influenced by topography, foliage, precipitation, buildings, and the antenna heights. These influences change significantly at the high frequencies that will be used to support the increased information flow to and from dismounted soldiers. The performance of advanced antenna technologies, such as phased arrays, and the signal processing and control complexity needed to attain a given level of performance depend largely on the characteristics of the radio path. Propagation measurements, modeling, and research on antenna technology are needed to characterize and quantify interactions of the environment and antennas.

IMPLEMENTATION GUIDELINES

The Army can count on several research objectives being met by commercial companies working for commercial ends. Objectives with specific military applications will require special attention by the Army to encourage commercial interest and, in some cases, will require Army investment.

Table 8-1 characterizes the 20 strategic research objectives identified by the committee. Near-term objectives are those for which research is urgently required to achieve goals set for Land Warrior systems on the digitized battlefield. Far-term objectives are those required to achieve a goal of energy sufficiency for the dismounted soldier in the Army After Next (after 2015). The column headed "Commercial Research Leverage" refers to objectives that will benefit from commercial R&D. The column headed Military-Specific Application refers to objectives unlikely to be pursued by commercial companies.

Of the 20 objectives identified, the committee believes that three research objectives have the most potential for balancing future energy demands and for increasing combat effectiveness by meeting power requirements of the dismounted soldier. These deserve immediate emphasis:

- wireless battlefield communications network
- models for optimizing energy efficiency
- advanced fueled systems

Wireless Battlefield Communications Network

As communications come to dominate the energy consumption of systems for the dismounted soldier, the creation of a virtual peer-to-peer architecture, as discussed in Chapter 6, will become increasingly important. Implementation of virtual peer-to-peer architecture will require much more than the straightforward adaptation of commercial technology. Although coding standards, some communications protocols, and a basic architecture might be borrowed from the wireless telephone and pager industry, the complexity of the Army's network will be heightened by the need for optimum reliability in extremely harsh communications environments characterized by high levels of interference, jamming, and unpredictable transmission paths. Building a network that can continue to operate when one or more nodes have been destroyed will require protocols that are not available commercially. The use of terrestrial or aerial repeaters to enable the transmission of digital data will require the development of complex and secure system software. Optimizing the distribution of information on the battlefield to eliminate unnecessary wireless traffic will require multidisciplinary thinking by experts in military doctrine, communications technology, speech and image coding, information presentation, and database management. The goal is to minimize energy consumption and electronic signatures while maximizing the combat soldier's effectiveness.

TABLE 8-1 Research Objectives

	Near Term	Far Term	Commercial Research Lever	Military-Specific Applications
Energy Sources and Systems				
Rechargeable batteries	X		X	X
Fuel cells	X			X
Advanced fueled systems[a]		X		X
Human-powered systems		X		X
Low Power Electronics and Design				
Design tools for minimizing power consumption	X		X	X
Architectural level design tools	X		X	X
Packaging to minimize interconnects		X	X	X
Submicron lithography		X	X	
Optimizing device design		X	X	
Design methodologies for Army "systems on a chip"		X	X	
Communications, Computers, Displays, and Sensors				
Terminal equipment architectures	X		X	X
Component and human computer interfaces		X	X	X
Ultra-low power displays and sensors		X		X
Multimodal and adaptive communication circuits	X		X	
Evolution of hardware and software		X	X	
Networks, Protocols, and Operations				
Wireless battlefield communications network[a]		X		X
Extending range of the dismounted soldier		X	X	X
Sensors and software for power management	X		X	X
Models for optimizing energy efficiency[a]	X	X	X	X
Propagation characteristics and antenna design		X		X

[a] Objectives with highest potential.

The Army should begin by assessing the state of the art of commercial communications technology. Simulations should be conducted of prospective communications architectures. The Army should not try to develop a completely separate communications system; instead, it should share the most costly aspects of the system, such as the development of UAV repeaters or steerable antenna technology, with the other military services, government agencies, and defense and commercial electronics industries. Cost and timeliness should be central considerations.

Models for Optimizing Energy Efficiency

The energy use of Land Warrior and successor systems for the dismounted soldier will depend on a host of variables, including electronic device technology, the characteristics of energy sources, processing algorithms, the communications architecture and protocols, sensors, and tactical and operational doctrine. Integrating this complex system and ensuring the greatest benefit per unit of energy consumption will require high fidelity models of the soldier's activities on the battlefield. These models will be invaluable planning aids and could provide an important check on the practicality of advanced doctrinal concepts.

The first step in devising a model should be to place instruments aboard prototype systems during tests and maneuvers to obtain an accurate picture of how the system is used. The instruments should measure the patterns of use of all energy-consuming subsystems, the functions of energy supplies, and the duty cycles of weapons and other equipment for a variety of mission types. Wireless communications, which promise to account for the major share of energy used, should be measured in detail. The physical load of ammunition, weapons, equipment, and food should be measured at intervals.

As the model is optimized, it could be used to determine trade-offs between an energy consuming subsystem, such as communications, and other equipment subsystems, such as the Land Warrior science and technology insertion candidates and other proposed capabilities. The model could help to measure and forecast progress in technology and could ultimately be used to derive dynamic estimates of optimal equipment loads and capabilities for various mission types.

Advanced Fueled Systems

The development of a hybrid system with fueled primary store has potential to revolutionize warfare as much or more than information technologies. Advanced fueled systems, including microturboalternators, TPVs (thermophoto-voltaics), and fueled system hybrids, will not only minimize the soldier's dependence on logistics, but will also provide power for any new electronics that are developed to enhance lethality or mobility in the interim. Because communication needs predominate, it is extremely important that development of a hybrid system matched to soldier communications needs, including low probability of detection, proceed in conjunction with the adaptation of wireless communication technologies to the battlefield.

FINDINGS

Based solely on an assessment of the energy efficiency characteristics of electronics currently in the Army inventory, the committee concluded that the Army's customary approach to acquiring military electronics equipment has resulted in systems that are strikingly less capable than commercial electronics with equivalent functions. Furthermore, commercial developers have learned that they can achieve other desirable military characteristics, such as reduced bulk, weight, and cost, through the active pursuit of higher energy efficiencies. The dismounted soldier, supported by the Land Warrior ensemble, will require electronics equipment with at least the same energy efficiency characteristics as commercial equipment. Army R&D must focus on translating energy efficiency into soldier effectiveness.

The most critical Land Warrior subsystem, the computer/radio subsystem, is handicapped by required system interfaces to existing communications systems. Technical hurdles imposed by the Army information systems architecture will have to be overcome before the design of the computer/radio subsystem can incorporate and benefit from ASIC and system on a chip technologies. This key subsystem is locked on a trajectory that lags behind commercial energy consumption trends, and the distance between them is growing steadily. In another decade, Army systems may well be characterized by specific energy consumption 100 times higher than it would be if commercial advances were incorporated.

Of the 20 significant research objectives recommended by the committee, the Army should place the most emphasis on:

- developing a wireless battlefield communications network
- developing models for optimizing energy efficiency
- developing advanced fueled systems keyed to the soldier system

In evaluating and determining priorities, energy efficiency must become the primary rationale for research on dismounted soldier systems. Capitalizing on experience with Land Warrior, the Army should use the following guidelines in implementing future programs:

- The Army must be willing to invest in new technology. The payoff in battery and other logistics (weight and bulk) savings should be considered to offset investment.
- Land Warrior technology should be considered separately from past investments. Research should not be constrained by the legacy of existing systems.
- Field and battle laboratories should be created to review and update Land Warrior operational requirements based on successful experiments with commercial equivalents.

- The vision is sound, but the science and technology insertion candidates for Land Warrior are aimed at the relatively near term. Advanced systems have not been identified that will meet the far-term power requirements.

9

Conclusions and Recommendations

This chapter summarizes the committee's main conclusions from its study of energy-efficient technologies and the Army's plans for the dismounted soldier. On the basis of each conclusion, the committee makes specific recommendations to meet the power requirements of dismounted soldiers.

Conclusion 1. The power requirements of the Land Warrior system will limit the effectiveness of dismounted soldiers on the digitized battlefield.

This study has shown that the Land Warrior system is far less energy-efficient than it could be. It will fall short of meeting the needs of the digitized battlefield principally because of excessive energy demands for computation and radio transmission. The Land Warrior program is on a course to field subsystems that are heavier, bulkier, and less functional than they would be using state of the art consumer technology. This is because the Army has failed to address energy efficiency in system and subsystem designs. The Land Warrior program provides for the incorporation of advanced technology, but the scope of necessary enhancements will require special funding and command emphasis by the Army.

Army developers of the Land Warrior system and its predecessor systems used energy consumption characteristics to allocate energy and to match energy consumption with battery capabilities. Energy efficiency, however, was not used as a defining requirement for specifying subsystems or for measuring the performance of Army contractors. To meet the requirements of the dismounted soldier, the energy consumption of human-portable systems will have to be stressed at every stage, from the determination of operational requirements to the design of microprocessors and computer and communications architectures.

Commercial equipment is available with the energy efficiencies the dismounted soldier needs. The Army cannot continue to rely primarily on improvements in energy storage, which only mask equipment inefficiencies. A coherent approach to prevent the problem from growing to crisis proportions will require concerted efforts by both the Army Acquisition Executive and the Army Materiel Command.

Recommendation 1a. Army leadership must emphasize the importance of reducing energy demand to achieve energy sufficiency for future dismounted soldiers. Meeting near- and far-term needs will require major changes in Army thinking. Paradigm shifts in energy strategy, system design, and the use of commercial technology are absolutely essential to avert a crisis. The new paradigms must be translated into top-down initiatives. Essential reforms include changes in the following areas:

- Energy Strategy. The Army must focus on energy consuming systems as well as on energy supplying systems.
- System Design for Efficiency. The Army must emphasize system integration at all levels so that the entire system can be optimized for energy efficiency. For example, modular hardware designs with dedicated processors are more energy-efficient than general-purpose computers. And communications architectures must be designed to distribute energy consuming components (sensors and processors) where they can most easily be served by local power sources.
- Use of Commercial Technology. Army systems must be closely coupled to the technologies used in commercial products. The Army must be fully capable of incorporating the most recent data-processing and communications technology into its systems.

Recommendation 1b. The Army should accelerate the development and insertion of enhancements to the Land Warrior system, focusing on improvements to the computer/radio subsystem, because the estimated power requirements for communications and computing functions in Land Warrior are clearly excessive.

Recommendation 1c. The Army Acquisition Executive should make energy efficiency a priority consideration in evaluating contractor performance in future procurements of electronics for the dismounted soldier.

Conclusion 2. Advanced fueled systems and energy-efficient technologies are both necessary to achieve energy sufficiency for soldiers in the Army After Next time frame.

Dramatic improvements in the energy efficiency of systems for the dismounted soldier are already available as a result of advances in low power electronics and commercial consumer technologies. Reducing energy consumption will mean that available energy sources will be able to support longer missions, using smaller and lighter energy sources, and that new functions can be added to increase the soldier's capabilities. Paying attention to energy consumption through equipment design, as well as increased awareness and enforcement of power discipline, will also yield ancillary benefits, including lighter components, reduced susceptibility to detection, lower cooling requirements, and simplified logistical support. These dramatic improvements, combined with limited increases in the specific energy of sources and improved storage capabilities afforded by advanced fueled sources, will make energy sufficiency possible for dismounted soldiers in the Army After Next even for the most problematic requirement, microclimate cooling.

Recommendation 2a. To achieve energy sufficiency, the Army should set research objectives that focus on energy-efficient technologies. Energy efficiency is the key to success for the Army After Next.

Recommendation 2b. The Army should support use of computer-aided design tools for systems and integrated circuits specifically optimized for low power performance. If the necessary design tools are not available commercially, the Army should support its own development programs, perhaps in conjunction with related DARPA efforts. Army contractors for electronic systems should be required to use energy-optimizing design tools.

Recommendation 2c. The Army should support the development of mission-specific software for dismounted soldier systems. General-purpose software is wasteful and not energy-efficient.

Recommendation 2d. The Army should support the development and use of low power software, in which each instruction is written or compiled to minimize power requirements. New tools may be required for specific military applications.

Recommendation 2e. The Army should use dedicated electronic circuits wherever possible to minimize power requirements. Application-specific integrated circuit (ASIC) technology can achieve the efficiencies of custom circuits and hardware and still be cost effective.

Recommendation 2f. The Army should establish and enforce standards of awareness and discipline for energy consumption in dismounted soldier operations.

Conclusion 3. Access to commercial technology must be improved.

The Army will not be able to meet the goal of digitizing the battlefield unless it improves its ability to adapt and benefit from commercial consumer technology. Subsystems in the Land Warrior system, for example, will be obsolete compared with commercially available consumer electronics before the system is fielded. Military radios that meet the strict definition of commercial off-the-shelf equipment in most cases are not built to the same energy efficiency standards as consumer electronics. The fact that Army developers or suppliers of military electronics also develop, produce, and market consumer electronics is no guarantee that advances in consumer electronics will be carried over into military systems. The committee found that the consumer and military business units of large corporations are substantially and deliberately isolated from each other and that technology used in military systems sometimes lags substantially behind the technology in consumer systems produced by the same company.

The Army, through the science and technology insertion component of the Land Warrior program, recognizes the need to build flexibility into the process for acquiring advanced technology. Institutional provisions for experimentation, such as the Advanced Warfighting Experiment at Fort Hood, and spiral developments providing for continuous design feedback, can accelerate the incorporation of applicable technologies.

Recommendation 3a. Army procurement strategy should include provisions for keeping pace with advances in the semiconductor industry. Even if it is fielded in increments, state-of-the-art technology should be fielded in small quantities so that systems can be upgraded frequently. In addition to requiring energy-efficient technologies, Army design and procurement contracts should require contractors to adopt improved technology automatically as it becomes available.

Recommendation 3b. The Army should support efforts to maintain the pace set by the National Technology Roadmap for Semiconductors. The road map is a key means of ensuring continued superiority in electronics technology by defining critical technology areas and research gaps that may stand in the way of needed breakthroughs. The Army should:

- Use the road map to project technology availability in specifying new systems.
- Support research and development in industry and universities in areas identified as critical in the road map.
- Contribute to the road map, either directly, through U.S. Department of Defense representation on the road map committee, or indirectly, through other members, such as representatives of the national laboratories.

Recommendation 3c. The Army should develop an effective strategy for keeping abreast of state of the art consumer product development and for specifying low power performance criteria in its solicitations. The Army should emphasize participation in consumer-oriented electronics industry activities that focus on low power electronics, such as conferences, symposia, and focus centers, as a way of raising awareness and expectations of energy-efficient performance. Only through participation can the Army keep abreast of technology development and, more important, influence industry priorities.

Recommendation 3d. The Army must experiment continuously to keep pace with the development of commercial equipment. Simulations should be used to determine the value of trade-offs between improvements in energy consumption and less essential equipment characteristics.

Conclusion 4. Wireless transmission will dominate energy demand in future dismounted soldier systems.

If the Army can take advantage of trends in commercial consumer electronics, the power requirements of computers, sensors, and displays for the dismounted soldier will fall to nearly negligible levels. Subsystems that perform these functions could consume less than 1 W of electricity by the year 2015. Energy needed for radio transmission will then dominate the power requirements for successor Land Warrior systems.

The cost of transmitting information, measured in terms of energy, depends largely on the range and frequency of transmissions. Video communications, which are emphasized in the Army's plans for digitizing the battlefield, are particularly demanding in terms of both bandwidth and distance. By adapting commercial communications equipment, the efficiency of DC-to-RF energy conversion can be increased from the range of 20 to 40 percent to the range of 50 to 70 percent in the foreseeable future. Communications architectures and protocols optimized for energy will yield even greater improvements.

Recommendation 4a. The Army should refine its requirements for high-resolution images and video communications to the minimum necessary to meet battlefield needs.

Recommendations 4b. The Army should minimize wireless data transmissions by reducing the time required to convey a given amount of information. Relevant technologies include speech and image compression, database caching, and information science technologies that reduce, eliminate, or automate the energy inefficient natural language (read message) transmissions that are currently used.

Recommendation 4c. The Army should adapt the hierarchical network architecture of cellular telephones to create a "virtual peer-to-peer" network, which would improve the distribution of computational resources while taking advantage of commercial cellular technologies.

Recommendation 4d. The Army should modify and synchronize operational doctrine with emerging systems to minimize soldier transmissions. For example, data collection and reduction should be performed as close to the data collector as possible, and computational components should be distributed across the network of soldier communicators. The Army should exploit energy saving communications protocols, such as the protocols used to alert radio receivers to incoming data in pagers and cellular phones. Other commercial techniques should be incorporated doctrinally to reduce or eliminate the operationaldemands on transmit energy.

Recommendation 4e. The Army should study alternatives for the military network design to optimize power consumption. For example, it should investigate the use of commercial low-orbit satellite systems and unmanned aerial vehicles as relatively energy-efficient alternatives that may also provide high-bandwidth capabilities.

Conclusion 5. Research to improve energy sources must continue.

Improved energy sources, with higher specific energies and better performance characteristics, will be important to the dismounted soldier because the proliferation of new electronics-based systems will continue. Unlike commercial investments in microelectronics and communications technologies, commercial investments in power sources and systems technologies will probably not be sufficient because the military market is small. Therefore, military research and development will still be needed.

In the near term, the dismounted soldier must rely on both nonrechargeable and chargeable batteries for power. But batteries will not suffice for missions that require more than a kilowatt-hour (about 20 hours using the initial Land Warrior system). For high energy (long mission time) requirements, fueled systems (generally, combinations of rechargeable batteries or capacitors charged by fuel cells or other fueled energy sources) can offer specific energy an order of magnitude higher than the best battery at relatively small development risk. Hybrid systems will make it possible to optimize performance for both high power and high energy requirements.

Recommendation 5a. For the near term, the Army should continue to support research and development on rechargeable batteries with specific energy higher than 200 Wh/kg.

Recommendation 5b. The Army should continue research into fueled energy sources and high-performance capacitors for use in hybrid energy supply systems for the dismounted soldier. It should develop prototypes of the most promising ones for field trials within the next decade.

Recommendation 5c. The Army should continue research for the far future across a broad range of technologies, including advanced fuel cells, microturbines, and thermophotovoltaic converters.

References

Abidi, A., A. Rofougaran, G. Chang, J. Rael, J. Chang, M. Rofougaran, and P. Chang. 1997. The future of CMOS wireless transceivers. Pp. 118–119 in Digest of Technical Papers, 1997 IEEE International Solid-State Circuits Conference, San Francisco, California , February 6–8, 1997. IEEE Catalog no. 97CH36014. Castine, Maine: John H. Wuorinen.

ADO (Army Digitization Office). 1995. Army Digitization Master Plan as of 30 January 1995. Washington, D.C.: Headquarters, Department of the Army.

AMC (Army Materiel Command). 1996. Minutes of the AMC Battery Summit meeting, June 4, 1996. Alexandria, Virginia: U.S. Army Materiel Command.

Army. 1995. C^4I Technical Architecture, Version 3.1. March 31, 1995. Arlington, Virginia: Department of the Army.

Arthur D. Little, Inc. 1996. Proceedings of the Fourth International Conference on Power Requirements for Mobile Computing and Wireless Communications, Santa Clara, California, October 1996. Available from Giga Information Group, One Long water Circle, Norwell, Mass. 02061.

Bass, J.C., N.B. Elsner, and F.A. Leavitt. 1994. The preliminary design of a 500 watt thermoelectric generator. Pp. 586–591 in Proceedings of the 29th Intersociety Energy Conversion and Engineering Conference. AIAA-94-4197-CP. Reston, Virginia.: American Institute of Aeronautics and Astronautics.

Benner, J.P., T.J. Coutts, and D.S. Ginley, eds. 1994. Proceedings of the First NREL Conference on the Thermophotovoltaic Generation of Electricity. AIP Conference Proceedings 321. Woodbury, N.Y.: AIP Press.

Benner, J.P., T.J. Coutts, and D.S. Ginley, eds. 1995. Proceedings of the Second NREL Conference on the Thermophotovoltaic Generation of Electricity. AIP Conference Proceedings 358. Woodbury, N.Y: AIP Press.

Butler, N., R. Blackwell, R. Murphy, R. Silva, and C. Marshall. 1996. Low cost uncooled microbolometer imaging systems for dual use. Pp. 583–591 in SPIE [Society of Photo-optical Instrumentation Engineers] Volume 2552. Bellington, Washington: International Society of Photo-optical Instrumentation Engineers.

Cairns, E.J. 1992. A new mandate for energy conversion: zero emission (electric) vehicles. Pp. 310–312 in Proceedings of the 35th International Power Sources Symposium, Cherry Hill, New Jersey, June 22–25. Piscataway, N.J.: Institute of Electrical and Electronic Engineers.

Chandrakasan, A.P., A. Burstein, and R.W. Brodersen. 1994. A low power chipset for multimedia applications. Pp. 82–83 in Proceedings of the 1994 IEEE International Solid-State Circuits Conference, San Francisco, California, February 24–27. Castine, Maine: John H. Wuorinen.

Chandrakasan, A.P. and R.W. Brodersen. 1995a. Minimizing power consumption in digital CMOS circuits . Proceedings of the IEEE 83(4): 498–523

Chandrakasan, A.P., and R.W. Brodersen. 1995b. Low Power Digital CMOS Design. Norwell, Mass.: Kluwer Academic Publishers.

Cook, C.I. 1994. Development of air interface standards for PCS. IEEE Personal Communications Magazine, 1(4):32–35.

Courtesy Associates. 1990. Fuel Cell Seminar, Phoenix, Arizona, November 25–28. Program and Abstracts. Washington, D.C.: Courtesy Associates.

Courtesy Associates. 1992. Fuel Cell Seminar, Program and Abstracts. Washington, D.C.: Courtesy Associates.

Courtesy Associates. 1994. Fuel Cell Seminar, Program and Abstracts. Washington, D.C.: Courtesy Associates.

Courtesy Associates. 1996. Fuel Cell Seminar, Program and Abstracts. Washington, D.C.: Courtesy Associates.

Crawford, Mark. 1996. Small power bite new display's big attraction. New Technology Week, September 3, 1996, p. 1.

Cressler, J., D. Harame, J. Comfort, J. Stork, B. Meyerson, and T. Tice. 1994. Silicon-germanium heterojunction bipolar technology: the next leap in silicon? Pp. 24–27 in Proceedings of the 1994 IEEE International Solid-State Circuits Conference, San Francisco, California, February 24–27. IEEE Catalog no. 94CH3410-8. Castine, Maine: John H. Wuorinen.

Dahbura, T. 1996. Trends in microprocessor performance and architecture. Paper presented at DARPA Workshop on Wearables in 2005, Arlington, Virginia., July 18–19. Sponsored by E.C. Urban.

Devasirvatham, D.M., R.R. Murray, H.W. Arnold, and D.C. Cox. 1993. Four-frequency CW measurements in residential environments for personal communications. IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC '93), Yokohama, Japan, September 8–11. Piscataway, N.J.: Institute of Electrical and Electronic Engineers.

Dickinson, A., B. Ackland, E.S. Eid, D. Inglis, and E.R. Fossum. 1995. A 256/spl time/256 CMOS active pixel image sensor with motion detection. Pp. 226–227 in Digest of Technical Papers, 41st IEEE International Solid-State Circuits Conference, February 15–17. IEEE Cat. No. 95CH35753. Castine, Maine: John H. Wuorinen.

Doney, M. 1996. Land Warrior System. Briefing by Michael Doney, U.S. Army, Project Manager-Soldier, to the Committee on Electric Power for the Dismounted Soldier, Washington, D.C. August 15, 1996.

Efkeman, E. 1996. Technology Thrust for the Individual Warrior. Briefing by Ed Efkeman, Research, Development and Engineering Center, U.S. Army Communications-Electronics Command, to the Committee on Electric Power for the Dismounted Soldier, Ft. Monmouth, New Jersey, October 29, 1996.

Federal Communications Commission. 1964. Rules and Regulations. Washington, D.C.: U.S. Government Printing Office. Vol III, part 73, pp. 167–253.

Flannery, R.E., and J.E. Miller. 1992. Status of uncooled infrared imagers. Pp. 379–395 in Infrared Imaging Systems. SPIE [Society of Photo-optical Instrumentation Engineers] Volume 1689 (1992). Bellington, Washington: International Society of Photo-optical Instrumentation Engineers.

Florida Educational Seminar. 1996. Proceedings of the Sixth International Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Boca Raton, Florida. Boca Raton: Paumanok Publications, Inc.

Forney, G.D., R.G. Gallager, G.R. Lang, F.M. Longstaff, and S.U. Qureshi. 1984. Efficient modulation for band-limited channels. IEEE Journal on Selected Areas in Communication 2(5): 632–647.

Gottesfeld, S., G. Halpert, and A. Landgrebe, eds. 1995. Proceedings of the First International Symposium on Proton Conduction Membrane Fuel Cells, Chicago, Illinois, October 8–13. Pennington, N.J.: The Electrochemical Society .

Griggs, J. 1997. Light infantry tests DSSU concepts: Dismounted Soldier System Unit displays actual view of battlefield. U.S. Army Training and Doctrine Command Force XXI Home Page. Available: http://204.7.227.75:443/f21home.html

IEEE (Institute of Electrical and Electronic Engineers). 1996. Proceedings of the 20th–25th Photovoltaics Specialists Conferences. Piscataway, N.J.: Institute of Electrical and Electronics Engineers.

IEEE Personal Communications Magazine. 1995. Special Issue: The European Path Toward UMTS. Vol. 2, no. 1.

Inside the Army. 1996. Army's technology scout scours Silicon Valley for new capabilities. October 21, p. 16.

Ivanenok, J.F., and T.H. Hunt. 1994. High voltage terrestrial AMTEC. Pp. 900–909 in Proceedings of the 29th Intersociety Energy Conversion and Engineering Conference. Paper no. AIAA-94-3903-CP. Reston, Virginia: American Institute of Aeronautics and Astronautics.

Killebrew, R.B. 1996. The Army After Next. Briefing by Col. Robert B. Killebrew, U.S. Army Training and Doctrine Command, to the Committee on Electric Power for the Dismounted Soldier, National Academy of Sciences, Washington, D.C., August 15, 1996.

Kinoshita, K., and E.J. Cairns. 1994. Fuel cells. Pp. 1098–1121 in Encyclopedia of Chemical Technology, vol. 2. New York: John Wiley & Sons.

Kinoshita, K., F.R. McLarnon, and E.J. Cairns. 1988. Fuel Cells: A Handbook. U.S. Department of Energy report no. DOE/METC-88/6096. Lawrence Berkeley Laboratory publication no. LBL PUB-644. Morgantown, W.V.: Morgantown Energy Technology Center.

Leiner, B.M., R.J. Ruth, and A.R. Sastry. 1996. Goals and challenges of the DARPA GloMo program. IEEE Personal Communications Magazine 3(6): 34–43.

Lemnios, Z., 1996. DARPA's Low Power Electronics Program. Briefing by Zachary J. Lemnios, Electronics Technology Office, Defense Advanced Research Projects Agency, to the Committee on Electric Power for the Dismounted Soldier, Washington, D.C., August 15, 1996.

MacLannan A. 1997. Personal communication from Alastair MacLannan, MELCOR Thermoelectrics, Trenton, N.J., to Deborah Jackson, member of the Committee on Electric Power for the Dismounted Soldier.

Marshall, L.T. 1996. Integrated Sight Modules TD. Briefing by Lawrence T. Marshall, U.S. Army Communications—Electronics Command Research, Development and Engineering Center, to the Committee on Electric Power for the Dismounted Soldier, Fort Monmouth, New Jersey, October 29, 1996.

McLarnon, F.R., and E.J. Cairns. 1989. Energy storage. Pp. 241–271 in Annual Review of Energy, vol. 14. Palo Alto, Calif.: Annual Reviews, Inc.

Megahed, S., B. Barnett, and L. Xie, eds. 1994. Rechargeable Lithium and Lithium-Ion Batteries. Proceedings Volume 94—28. Pennington, N.J. : The Electrochemical Society.

Meindl, J.D. 1995.Low power microelectronics: retrospect and prospect. Proceedings of the IEEE 83(4): 619–635.

Meng, T. 1997. Personal communication from Prof. Teresa Meng, Stanford University, to Deborah Jackson, member of the Committee on Electric Power for the Dismounted Soldier, November, 1997.

Nixon, R.H., S.E. Kemeny, C.O. Staller, and E.R. Fossum. 1996. 256/spl times / 256 CMOS active pixel sensor camera-on-a-chip. Pp. 178–179, 440, in Digest of Technical Papers, 42nd IEEE International Solid-State Circuits Conference, February 8–10. IEEE Cat. No. 96CH35889. Castine, Maine: John H. Wuorinen.

NRC (National Research Council). 1988. Mobile Electric Power Technologies for the Army of the Future. Energy Engineering Board. National Research Council. Washington, D.C.: National Academy Press.

NRC. 1993a. STAR 21: Strategic Technologies for the Army of the Twenty-First Century. Technology Forecast Assessments. Board on Army Science and Technology. National Research Council. Washington, D.C.: National Academy Press.

NRC. 1993b. STAR 21: Strategic Technologies for the Army of the Twenty-First Century. Special Technologies and Systems. Board on Army Science and Technology. National Research Council. Washington, D.C.: National Academy Press.

NRC. 1995. The Global Positioning System: A Shared National Asset. Commission on Engineering and Technical Systems. Washington, D.C.: National Academy Press.

NRC. 1997. Tactical Displays for Soldiers: Human Factor Considerations. Committee on Human Factors. Commission on Behavioral and Social Sciences and Education. Washington, D.C.: National Academy Press.

Ohmi, T. 1994. Scientific semiconductor manufacturing based on ultra clean processing concept. Pp. 3–22 in Proceedings of the International Conference on Advanced Microelectronic Devices and Processing, Sendai, Japan, February 28—March 4. Sendai: Tohoku University.

Pottie, G. 1995. System design choices in personal communications. IEEE Personal Communications Magazine 2(5):50–68. October.

Rapeli, J. 1995. UMTS: Targets, system concept, and standardization in a global framework. IEEE Personal Communications Magazine 2 (1):20–28. February.

Raskovich, E., ed. 1993. Front End Analysis of Soldier Individual Power Systems. USA-BRDEC-TR//2541. Ft. Belvoir, Va.: Ft. Belvoir Research, Development and Engineering Center. May.

Rowe, D.M., ed. 1988. Proceedings of the First European Conference on Thermoelectrics. Stevengate, Hertsfordshire, U.K.: Peter Peregrinus, Ltd.

Sass, P.F., and L. Gorr. 1995. Communications for the digitized battlefield of the 21st century. IEEE Communications Magazine 33(10): 86–95.

Seaton, S. 1997. Personal communication from Scott Seaton, Program Director, Situation Systems, SRI, to D. Siewiorek, member of the Committee on Electric Power for the Dismounted Soldier, July.

Shahani, A.R., D.K. Schaeffer, and T.H. Lee. 1997. A 12 mW wide dynamic range CMOS front end for a portable GPS receiver. Pp. 368–369, 487, in Digest of Technical Papers, IEEE International Solid-State Circuits Conference, 43rd ISSCC, February 6–8. IEEE Cat. No. 97CH36014. Castine, Maine: John H. Wuorinen.

SIA (Semiconductor Industry Association) 1994. The National Technology Roadmap for Semiconductors. San Jose, Calif.: Semiconductor Industry Association. Updated version to be published in fall 1997.

Siewiorek, D., C.G. Bell, and A. Newell. 1982. Computer Structures: Principles and Examples. New York: McGraw-Hill.

Singh, D., J. Rabaey, M. Pedram, F. Catthoor, S. Rajgopal, N. Sehgal, and T. Mozdzen. 1994. Power conscious CAD tools and methodologies: a perspective. Proceedings of the IEEE 83(4): 570–594.

Smailagic, A., and D.P. Siewiorek. 1996. Modalities of interaction with CMU wearable computers. IEEE Personal Communications 3(1): 14–25.

Space Power Institute. 1990. Mobile Battlefield Power Workshop. M.F. Rose, ed. Results of a workshop held in Durham, North Carolina, October 30–November 1, 1990. 2 vols. Sponsored by the Army Research Office, Contract No. DAAL03-86-D-001. Prepared by Space Power Institute, Auburn University, Auburn, Alabama.

Space Power Institute. 1992a. RTG Power Applications Workshop. M.F. Rose, ed. Results of a workshop held in Park City, Utah, March 22–25, 1992. Sponsored by the Army Research Office, the U.S. Department of Energy, and NASA Jet Propulsion Laboratory. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1992b. Prospector III: High Energy Density—High Power Density Power Sources R&D Workshop. M.F. Rose, ed. Results of a workshop held in Auburn, Alabama, May 26–28, 1992. Sponsored by the Army Research Office. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1992c. Prospector IV: Small Engines and Their Applicability to the Soldier System Workshop. M.F. Rose, ed. Results of a workshop held in Durham, North Carolina, November 10–12, 1992. Sponsored by the Army Research Office. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1994. Prospector VII: Small Fuel Cells for Portable Power Workshop. C.R. Johnson and M.F. Rose, eds. Results of a workshop held in Durham, North Carolina, October 31–November 1, 1994. Sponsored by the Space Power Institute and the Army Research Office. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1996. Prospector VIII: Thermophotovoltaics—An Update on DoD, Academic, and Commercial Research. C.R. Johnson and M.F. Rose, eds. Results of a workshop sponsored by the Army Research Office, Durham, North Carolina, July 14–17, 1996. Auburn, Alabama: Space Power Institute.

SPC (System Planning Corporation). 1994. Micro-electromechanical Systems (MEMS): An SPC Market Study. System Planning Corporation, Arlington, Virginia.

Staba, J. 1996. PCS for the Soldier. Briefing by Joseph Staba, U.S. Army Communications—Electronics Command Research, Development and Engineering Center, to the Committee on Electric Power for the Dismounted Soldier, Ft Monmouth, New Jersey, October 29, 1996.

Starner, T. 1996. Human-powered wearable computing. IBM Systems Journal 35(384): 618–619.

Tan, C., Y. Tzeng, I. Waitz, R. Walker, D.J. Orr, S. Senturia, A. Ayon, J. Mur Miranda, E. Piekos, C. Lin, A. Epstein, M. Spearing, G. Anathasuresh, K. Breuer, K.S. Chen, F. Ehrich, E. Esteve, G. Gauba, S. Jacobson, J. Lang, A. Mehta, S. Nagle, and M. Schmidt. 1997. Micro Gas Turbine Generators. Interim technical progress report for Grant DAAH 04-95-1-0093, Army Research Office, Research Triangle Park, North Carolina.

TRADOC (U.S. Army Training and Doctrine Command). 1994a. Land Warrior Operational Requirements Document. April 13, 1994. Ft. Monroe, Virginia: U.S. Army Training and Doctrine Command.

TRADOC. 1994b. Force XXI Operations: A Concept for the Evolution of Full-Dimensional Operations for the Strategic Army of the Early Twenty-First Century. TRADOC Pamphlet 525-50. Washington, D.C.: U.S. Government Printing Office.

Zucchetto, J.J., P.S. Myers, J.H. Johnson, and T. Johns. 1989. Mobile Electric Power Technologies for the Army of the Future. Society of Automotive Engineers Technical Paper 891876. Warrendale, Pennsylvania: Society of Automotive Engineers.

Appendices

Appendix A

Meetings and Activities

Committee members met with representatives of the Army and other organizations many times. Five meetings were held in the facilities of the National Academy of Sciences and National Research Council in Washington, D.C. Two fact-finding sessions were hosted by the U.S. Army Communications-Electronics Command Research, Development and Engineering Center at Fort Monmouth, New Jersey. A third fact-finding session was hosted by the Motorola Government Systems Group in Scottsdale, Arizona. Specific briefings included:

Twenty-First Century Land Warrior
Maj.Marc Collins
Acting Product Manager
Project Manager—Soldier

Land Warrior Science and Technology Component
Mr.Patrick R.Snow,Jr.,Manager
Force XXI Land Warrior Program
Natick Research,Development and Engineering Center, Soldier System Command

Land Warrior Operational Requirements
Lt.Col.Patrick J.Berger
TRADOC System Manager—Soldier
Infantry Center and School

Land Warrior Description
Mr.Michael Doney
Project Manager—Soldier

System Assumptions and Power Profiles
Mr.Michael Doney
Project Manager—Soldier

Technology Insertion Candidates
Mr.Bradford Laprise
Force XXI Land Warrior Program Office

Land Warrior Functional Demonstration
Sgt.Scott Decker
TRADOC System Manager—Soldier
Infantry Center and School

Generation II Soldier Power Management Findings
Mr.James Hamilton
Motorola Space and Systems Technology Group
Force XXI Land Warrior Program Office

Computer Design Innovations
Dr.Daniel P.Siewiorek
Professor,Carnegie-Mellon University
Member,Committee on Electric Power for the Dismounted Soldier

The Army After Next
Col.Robert B.Killebrew
U.S.Army Training and Doctrine Command

War on Power Drain
Mr.Walter Davis
Vice President,Motorola Corporation
Member,Committee on Electric Power for the Dismounted Soldier

Power Management Research and Development
Mr.Zachary J.Lemnios
Electronics Technology Office
Defense Advanced Research Projects Agency

Research, Development and Engineering Center Reengineering and Business Strategies
Mr.Jan Moren,Director,
Advanced Systems Directorate
Communications-Electronics Command

Primary/Rechargeable Batteries Development
Dr.Harold A.Christopher,Chief,
Battery Development and Engineering Branch,Power Sources
Division,Communications-Electronics Command

Future Vision on Power Needs for the Army After Next
Mr.John Klevecz
TRADOC Technology Consultant
Science Applications International Corporation

Army Research Office Power Program on Fuels Cells and Thermophotovoltaics
Dr. Richard J. Paur
Chief,Electrochemistry and Advanced Energy Conversion
Army Research Office

Communications-Electronics Command (CECOM)
Power Center of Excellence and Power Sources
Program
Dr.Robert P.Hamlen
Director,Power Center of Excellence
Communications-Electronics Command

Ft. Belvoir Fuel Cell and Engineer Generator Program
Mr.James R.Carlson
Mr.Richard Jacobs
Communications-Electronics Command

Army Research Laboratory
Battery and Fuel Cell Research Program
Dr.Sol Gilman
Chief,Electrochemistry Branch
Sensors and Electron Devices Directorate
Army Research Laboratory

Army Research Laboratory Battery and Fuel Cell Research Program
Mr.Mark Salomon
Research Chemist
Army Research Laboratory

Army Research Laboratory Battery and Fuel Cell Research Program
Dr.Michael Binder
Research Physical Scientist
Army Research Laboratory

Program on Microturbine Engines
Dr.Alan H.Epstein
Professor,Aeronautics and Astronautics
Massachusetts Institute of Technology

Overview and Insight
Mr.Robert Giordano
Director,Research,Development and Engineering Center
Communications-Electronics Command

Army Technical Architecture
Mr.Paul C.Manz
Senior System Engineer
Army Systems Engineering Office

Common Operating Environment
Dr.David Usechak
Project Manager — Common Software

Tactical Displays Technology
Mr.M.Robert Miller
Chief,Displays Branch
Sensors and Electronic Devices Directorate
Army Research Laboratory

Electrochemical Ultracapacitors
Dr.T.Richard Jow
Research Physical Scientist
Sensors and Electron Devices Directorate
Army Research Laboratory

Networks and Protocols
Mr.Charles Graff
Space and Terrestrial Communications Directorate
Research,Development and Engineering Center
Communications-Electronics Command

Global Mobile Information Systems
Mr.Robert Ruth
Defense Advanced Research Projects Agency

Digital Integrated Laboratory Presentation
Dr.Myron Holinko
Director,Digital Integrated Lab
Research,Development and Engineering Center
Communications-Electronics Command

Technology Thrust for the Warrior
Mr.Ed Efkeman
Research,Development and Engineering Center
Communications-Electronics Command

Hand-Held Multimedia Terminal
Mr.Charles Strimpler
Space and Terrestrial Communications Directorate
Research,Development and Engineering Center
Communications-Electronics Command

Soldier Terrestrial PCS
Mr.Joseph Staba
Space and Terrestrial Communications Directorate
Research,Development and Engineering Center,
Communications-Electronics Command

Low Power Electronics and Power Management
Mr. Robert H.Sproat
Advanced Systems Directorate
Research,Development and Engineering Center, Communications-Electronics Command

Advanced Warrior Technologies and Systems
Mr. Erling E.Rasmussen
Corporate Vice President and Assistant General Manager
Space and Systems Technology Group
Motorola

Power Drain Philosophy and Paging Applications
Mr.Jerry Brand
Space and Systems Technology Group
Motorola

SINCGARS Issues
Mr.Doug Antisell
Project Manager — Tractical Radio Communications Systems
Communications-Electronics Command

Overview and Performance of Complex Arithmetic Processors
Ms.Susan Gilfeather
Principle Engineer
Space and Systems Technology Group
Motorola

Modular Multifunction Information Transfer Systems
Dr.Bruce Fette
Chief Engineer of Signal Processing
Space and Systems Technology Group
Motorola

Information Distribution Technology
Dr.Samuel C.Chamberlain
Army Research Laboratory

Appendix B

Sample Estimate of Operational Requirements for Land Warrior

Operational requirements for Land Warrior were developed by the Infantry Center in terms of wartime and peacetime operational mode summaries for each Land Warrior subsystem (TRADOC, 1994). As shown in Table B-1, the baseline list of electronics includes a computer, soldier and squad radios, a Global Positioning System terminal, a video capture device, hand-held and helmet-mounted displays, a laser detector, an image intensifier, a laser rangefinder and aiming light, a digital compass, a thermal weapons sight and close combat optic, and a video camera. These are grouped into a computer/radio subsystem, an integrated helmet assembly subsystem, and a weapon subsystem.

Table B-1 also lists the power requirements of the objective Land Warrior system. To estimate these power requirements, the Army defined characteristic mission profiles for each subsystem and then compiled summaries for various operational modes. The wartime operational mode summary tabulated mission profile data defined for various wartime missions for dismounted soldiers, including military operations in urban terrain (MOUT) attack, night attack, MOUT defense, open terrain defense, rear area operations, and civil affairs support. Peacetime summaries were also compiled, based on mission profiles defined for such things as the Army Training and Evaluation Program and Command Post exercises, squad and platoon field training exercises, night training, and live-fire exercises.

An example is the mission profile for the laser rangefinder in an attack in urban terrain (Table B-2). The profile lists each task, the number of occurrences, the time required to perform the task, and the total operating time. This mission profile, which requires 19.54 minutes (0.33 hours) operating time, became part of the wartime operational mode summary for the laser rangefinder (Table B-3).

The Army estimated annual wartime usage by using a baseline planning factor of 30 iterations per year of a 12-day combat scenario. During each iteration, units equipped with the Land Warrior ensemble would participate in 138 hours of operations, as shown in the operational mode summary, with the balance of time being used for rest, refitting, and preparation for the next iteration.

TABLE B-1 Power and Energy Requirements for the Land Warrior System

	Cumulative Peak Power (W)	Function Operating Power (W)	Standby (Alert) Power (W)	Operating Duty Cycle (%)	Average Operating Power (W)	12-Hour Mission Energy Goals (Wh)
Computer/ Radio Subsystem						
Computer	18.40	14.80	1.48	Table 5-2	8.27	99.24
Hand-held flat panel display	7.70	6.40	0.00	5	0.32	3.84
Soldier radio						
Receive	1.70	1.40	1.00	40	1.06	12.72
Transmit	7.20	6.00	0.00	20	1.20	14.40
Squad radio						
Receive	2.40	2.00	1.00	20	1.20	14.40
Transmit	14.40	12.00	0.00	10	1.20	14.40
Global Positioning System	1.80	1.50	0.60	45	1.01	12.06
Video capture	1.20	1.00	0.00	15	0.15	1.80
Integrated Helmet Assembly Subsystem (IHAS)	5.8 (night)	5.6 (day)	0.25	Table 5-10	2.82	33.84
Helmet-mounted display						
Image intensifier with integrated flat panel display						
Laser detectors						
Weapon Subsystem	7.80	6.00	0.00	Table 5-9	2.78	33.36
Laser rangefinder						
Laser aiming light						
Digital compass						
Thermal weapon sight						
TOTALS	68.4	56.7	—	—	20.0	240

In Table B-3, A_t is the time per iteration that the subsystem is active, and C_t is the computer operating time. Because nearly all Land Warrior electronics depend on the computer, an annual Land Warrior system operating time of up to 2,643.6 hours was calculated based on the computer operational mode summary.

TABLE B-2 Attack Mission Profile for the Laser Rangefinder

Task/Event	Number of Occurrences	Time for Each Task (minutes)	Total Operating Time (minutes)
Unstow	4	0.03	—
Switch on	4	0.05	0.20
Warm up	4	0.05	0.20
Focus	37	0.05	1.85
Adjust diopter	7	0.08	0.56
Observe	7	2.15	15.05
Trigger/fire	37	0.02	0.74
Read	37	0.02	0.74
Switch off	4	0.05	0.02
Optical zero	1	0.03	—
Change battery	0	0.75	—
Perform preventive maintenance	1	0.50	—
Stow	4	0.03	—
TOTAL			19.54

TABLE B-3 Wartime Operational Mode Summary for the Laser Rangefinder

Mission	Number of Lasings	Operating Time (hours)	A_t (hours)	C_t (hours)
Attack (MOUT)	37	0.33	11.06	12
Defense (MOUT)	27	0.30	7.29	8
Attack (night)	42	0.40	14.79	16
Defense	33	0.07	5.62	6
Rear area operations	97	1.44	44.10	48
Civil affairs support	129	1.40	44.13	48
TOTALS	365	3.94	126.99	138

REFERENCES

TRADOC (U.S. Army Training and Doctrine Command). 1994. Land Warrior Operational Requirements Document, April 13, 1994. Ft. Monroe, Va.: U.S. Army Training and Doctrine Command.

Appendix C

Energy Source Technologies

BATTERIES

Although batteries in general represent a very large, mature product class in commercial production, enormous improvements in specific power, specific energy, and cycle life (for rechargeable batteries) have been made in the past decade (Space Power Institute, 1990, 1992b). Much of the driving force for the technical improvements has come from the rapid growth of portable computers, cellular telephones, and other communication devices. However, very few of these improvements have been of direct benefit to communication devices used by the Army.

Battery production worldwide is approximately $40 billion (Salkind, 1996) with U.S. production at about $11 billion. Military purchases are only a small percentage of the total, and there appears to be little interest among large manufacturers in producing military batteries.

Improving the specific energy (available energy from a fixed mass) and energy density (available energy from a fixed volume) of batteries have been commercial goals. But because most commercial devices require only a few AA cells, weight reduction has been second in importance to energy capacity. As shown in Figure C-1, the capacity of AA nickel alkaline (NiCd and NiMH) batteries has risen from 0.4 Ah to 1.2 Ah in the past 20 years. Very fast recharging (in less than 1 hour) has also become available. Lithium rechargeable systems in the same size packaging have approximately the same capacity, but at much higher voltages, resulting in cells with higher specific energy. However, so far lithium rechargeable cells cannot be recharged quickly. Improvements continue to be made.

Among the Army's options for keeping pace with these rapid changes is the adaptation of commercially available cells. Current military battery systems could be replaced by systems with different voltage characteristics as long as the new system volume is the same or smaller. This should be possible with new, more efficient techniques for DC-DC conversion, which would eliminate the problem of Army communication devices being locked into using power sources with particular voltage levels.

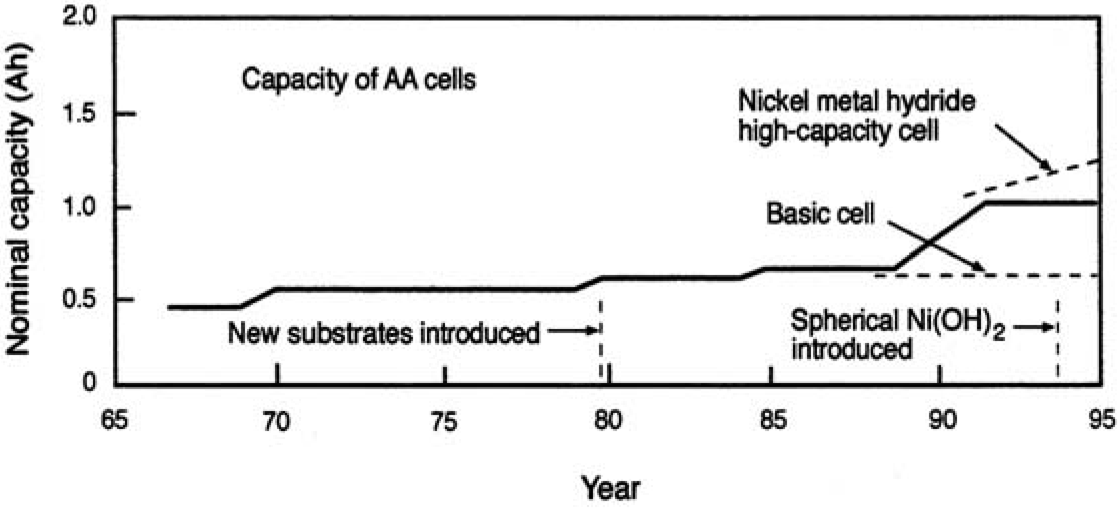


FIGURE C-1 Chronological improvements in the capacity of AA nickel batteries.

The performance characteristics and production levels of the common primary, secondary, and special battery systems considered in this report are listed in Tables C-1, C-2, and C-3.

Systems Likely to Meet the Needs of the Dismounted Soldier

Of the more than 30 rechargeable battery systems in commercial production or in advanced development, only seven or eight seem likely to meet the military goals of availability in small sealed cells with appropriate levels of safety, reliability, and low temperature and high temperature performance. These few systems are described in this section, with estimates of their present performance levels and estimates of what might be achieved in five and ten years. The research needed to achieve the listed goals is also briefly described.

Although a low temperature requirement of -40°C is still listed in some Army documents, the committee was informed that this temperature requirement was principally for storage. For operations, the committee assumed a minimum temperature requirement of -25°C but even this may be unrealistically low and may disqualify otherwise practical systems.

The systems likely to provide the desired combination of compactness, specific energy, and specific power fall into two categories: rechargeable alkaline electrolyte systems (nickel-metal hydride, nickel-zinc, MnO_2-zinc) and rechargeable lithium electrode systems (lithium metal anodes, lithium intercalating anodes, lithium alloy anodes [including the tin oxide type]).

TABLE C-1 Summary of Primary Battery Data

			Theoretical			Working			
Battery System	Anode	Cathode	Voltage	Ah/kg	Wh/kg	Voltage	Wh/kg	Wh/l	Production Value[a]
Lechlanche (zinc-carbon)	Zn	MnO_2	1.6	224	358	1.5	85	165	vl
Magnesium	Mg	MnO_2	2	271	758	1.75	100	195	vs
Alkaline	Zn	MnO_2	1.6	224	336	1.25	125	330	vl
Mercury	Zn	HgO	1.34	190	255	1.3	100	470	vvs
Silver (silver-zinc)	Zn	Ag_2O	1.5	180	288	1.45	120	500	ss
		AgO	1.85	270	445	(2 plateaus)	140	650	
Zinc-air	Zn	O_2(air)	1.65	658	1,066	1.25	500	1,050	1
Aluminum-air	Al	O_2(air)	2.7	2,980	8,046	1.1	300	240	vs
Lithium Systems									
Sulfur dioxide	Li	SO_2	3.1	379	1,175	2.8	260	415	1
Thionyl chloride	Li	$SOCl_2$	3.66	407	1,489	3.3	320	700	1
Sulfuryl chloride	Li	SO_2Cl_2	3.9	360	1,405	3.7	450	900	vvs
Manganese dioxide	Li	MnO_2	3.5	286	1,001	2.8	230	550	vl
Carbon monofluoride	Li	$(CF)_x$	3.1	703	2,180	2.5	250	600	l
Iron disulfide	Li	FeS_2	1.8	725	1,304	1.4	130	400	l

[a] Key: vl = ≥ $1 billion
l = $100 million to $1 billion
s = $10 million to $100 million
vs = 8 $10 million
vvs = 8 $2 million

Improvements

MnO_2 cathode material improvements can increase nonlithium system capacity by as much as 15 percent.
Improvements in separator material and technology can increase stability and rate of all primary cells.
Air electrode improvements can increase power capability of air cathode systems.
Safety for all lithium battery systems can be improved with improvements in separators.
Packaging technology can increase specific energy of Li/MnO_2 technology.
MnO_2 cathode material improvements can increase capacity and discharge rate in lithium systems.

Focus Chemistries

Zn, Mg/MnO_2, and Li/FeS_2 are commercial market driven.
Zinc-air, Li/MnO_2, and Li/CT_x are areas of interest for the government because they have either high specific power or high specific energy or both.

TABLE C-2 Summary of Rechargeable Portable Battery Data

			Theoretical			Working				
Battery System	Negative Electron	Positive Electron	Voltage	Ah/ kg	Wh/ kg	Voltage	Wh/ kg	Wh/ l	Production Value[a]	Estimated Life (Cycles)
Lead-acid	Pb	PbO_2	2.1	83	175	2.0	35–50	85	vl	400
Nickel-iron	Fe	NiOOH	1.4	224	313	1.2	35–60	70	vs	500
Nickel-cadmium	Cd	NiOOH	1.35	181	244	1.2	35–52	75	vl	600
Nickel-zinc	Zn	NiOOH	1.73	215	372	1.6	65–80	150	s	400
Silver-zinc	Zn	AgO	1.85	283	524	1.5	90–150	180	vs	100
Nickel-hydrogen	H_2	NiOOH	1.5	269	434	1.4	55–60	60	S	600
Nickel-metal hydride	Mhx 1.2 to 2 w/o H	NiOOH	1.35	206	278	1.2	55–70	120	vl	800
Silver-cadmium	Cd	AgO	1.4	227	318	1.2	60–80	110	vvs	200
Zinc-bromine[b]	Zn	Br Complex	1.85	139	258	1.55	70	60	vvs	400
Alkaline manganese	Zn	MnO_2	1.6	224	330	1.2	55	250	vl	15
Zinc-air	Zn	O_2 (air)	1.6	658	1,085	1.15	110	130	vs	25
Lithium Systems										
$LiMn_2O_4$	Li	Mn_2O_4	4	143	510	3.7	140	300	vs	250
$LiNiO_2$	Li	NiO_2	4.2	137	575	3.6	155	325	res	—
$LiCoO_2$	Li	CoO_2	4.2	178	750	3.7	95	235	vs	250
Li/ organosulfide	Li	R-S-S-R	3	~300	~900	2	200 est	300 est	res	300
Li/ organosulfide	Li	$(CS)_x$	2	~400	~800	2	200 est	300 est	res	300

[a] Key: vl = ≳ $1 billion
l = $100 million to $1 billion
s = $10 million to $100 million
vs = 8 $10 million
vvs = 8 $2 million
res = research

[b] Not portable.

			Theoretical			Working				
Battery System	Negative Electron	Positive Electron	Voltage	Ah/kg	Wh/kg	Voltage	Wh/kg	Wh/l	Production Value[a]	Estimated Life (Cycles)
$LiMn_2O_4$	Li+C	Mn_2O_4	4/3	102	356	3.7	70–100	170	res	—
$LiNiO_2$	Li+C	NiO_2	4.2/3	100	360	3.6	70–100	170	res	—
$LiCoO_2$	Li+C	CoO_2	4.2/3	100	360	3.7	70–100	170	1	1,000
Polymer	Li+C	Mn_2O_4	4/3	102	358	3.0	150 est	300 est	vvs	300
Large iron sulfides	Ll(Al)	FeS/ FeS_2	1.33/1.73	285/345	459/514	1.3/1.6	100/180	200/350	res	~1,000

[a] Key: vl = ≥ $1 billion

l = $100 million to $1 billion

s = $10 million to $100 million

vs = 8 $10 million

vvs = 8 $2 million

res = research

[b] Not portable.

Improvements

Charger and charging methods can improve cycle life and safety of rechargeable cells.

Improvements in NiOOH and separator technology can increase capacity of all nickel systems.

Improvements in metal hydride anode can increase the energy by nearly 2 times (Mhx 1.2 to 2 w/o H).

Material improvements can increase cycle life of rechargeable alkaline battery.

Material improvements can increase cycle life of rechargeable zinc-air battery.

Air cathode improvements can increase power capability and cycle life of the zinc-air system.

Safety for all rechargeable lithium batteries can be improved with improvements in separators.

Anode material improvements for lithium ion and lithium polymer batteries can increase the specific energy and safety.

Cathode material improvements can increase specific energy of all lithium batteries.

Focus Chemistries

Nickel-metal/hydride, alkaline, and zinc-air are market driven; thus, unique military requirements may be overlooked.

Lithium systems focus on military-unique requirements.

Zn, Mg/MnO_2, and Li/FeS_2 market driven.

TABLE C-3 Summary of Data on Reserve, Thermal, and High Temperature Rechargeable Batteries

Battery System	Anode	Cathode	Working Voltage	Wh/kg	Wh/l	Estimated Life (Cycles)
Reserve						
Water activated	Mg or Zn	CuCl	1.5–1.6	65	125	(Not rechargeable)
		MnO_2	1.5–1.6	65	125	
		AgCl	1.5–1.6	125	250	
		Others				
Spin activated[a]	Pb	PbO_2	1.5			(Not rechargeable)
	Zn	AgO	1.4			
	Li	$SOCl_2$	3.5			
	Li	FeS_2	1.8			
Electrolyte introduction-activated	Zn	AgO or Ag_2O	1.6	50	160	(Not rechargeable)
	Li	V_2O_5	3.3	50	100	
	Li	SO_2	3	120	200	
	Li	$SOCl_2$	3.5	150	300	
Thermal batteries	Ca	$CaCrO_4$	2.4	30	40	(Not rechargeable)
	Mg	V_2O_5	2.5			
	Li	FeS_2	1.8	40	100	
High temperature rechargeable batteries						
Lithium-iron-sulfide	Li	FeS	1.3	100	200	700
		FeS_2	1.6	180	350	1,000
Sodium-sulfur	Na	S	2.1	170	250	100–2,000
Sodium-nickel chloride	Na	$NiCl_2$	2.58	90	160	600–1,000

[a] These batteries are not designed to be weight or volume efficient.

TABLE C-4 Nickel Metal Hydride Battery Systems

Present Advantages	Present Disadvantages	5 Years	10 Years
Higher specific energy than NiCd	Lower specific power than NiCd	Higher rate capability, 25% more capacity per volume	40% capacity improvement per volume
Rapid recharge at room temperature	Poor charge retention, 5% per week loss at room temperature	Charge loss reduced to 2% per week at room temperature	—
Long cycle life	Poor thermal stability Poor overcharge recombination kinetics	Lower vapor pressure alloys	Lower vapor pressure alloys
Maintenance free	—	—	—

Rechargeable Alkaline Electrolyte Systems

Most anode battery systems can be assembled with various cathodes and electrolytes in combinations described in the Tables C-4 through C-15. These tables present a summary of the candidates likely to meet the future power requirements of the dismounted soldier. Each table summarizes the advantages and disadvantages of each chemistry, as well as technological projections of what can be accomplished in five and ten years.

Improvements in nickel metal hydride battery systems are shown in Table C-4. The anticipated improvements will require sustained research in the following areas:

- metal hydride alloys for better thermal stability
- cathode materials with improved volumetric efficiency (e.g., nanostructured, fibrous, and higher valence materials)
- charge profile with optimum charging, overcharge recombination kinetics
- better separators

Improvements in rechargeable alkaline manganese dioxide battery systems are shown in Table C-5. To achieve the projected improvements, it will be necessary to research the following areas in depth:

- materials for better cycle life and low temperature performance (nanostructured, catalytic MnO_2, improved carbons and graphites)
- improved cellophane (or other separator) for higher rate performance
- optimal recharging profile

TABLE C-5 Rechargeable Alkaline Manganese Dioxide (RAM) Battery Systems

Present Advantages	Present Disadvantages	5 Years	10 Years
Low cost	Lower specific power	Improved rate	Improved cycle life
Maintenance free	Poor cycle life	Improved cycle to cycle capacity	Improved low temperature operation
Good charge retention	Decreasing capacity with cycle life and depth of discharge	—	—
	Poor low temperature performance	—	—

Improvements in metal zinc battery systems are shown in Table C-6. To achieve the projected improvements, major research will be needed in the following areas:

- cathode materials for improved volumetric efficiency (e.g., nanostructured, fibrous, higher valence)
- lightweight current collectors for the nickel electrode
- charge profile for optimal charging, overcharge recombination kinetics
- better separators, microporous membranes, and cellulosic films
- complex electrolytes for improved cycle life

TABLE C-6 Nickel Zinc (NiZn) Battery Systems

Present Advantages	Present Disadvantages	5 Years	10 Years
Higher specific energy than NiCd	Poor overcharge recombination kinetics	Higher specific power, 10% more capacity per volume	20% specific energy improvement per volume
Maintenance free	—	—	—
Rapid recharge	Moderate charge retention; 2% per week at room temperature	Charge loss reduced to 1% per week at room temperature	—
Moderate cycle life	—	Improved separator and electrolytes; 500–800 cycles	Improved separator and electrolytes; 800–1000 cycles

TABLE C-7 Lithium Batteries with Lithium Metal Anode Structures

Present Advantages	Present Disadvantages	5 Years	10 Years
Highest energy and power capability	Safety	Improved safety and cycle life through improved electrolytes	—
	Poor cycle life		
	No tolerance to overcharge and overdischarge		

Rechargeable Lithium Systems

Lithium systems offer the most promise in terms of specific energy (energy per unit weight). Lithium chemistry, however, raises serious safety and environmental concerns. Even though lithium systems as presently fabricated have no tolerance to overcharging or overdischarging, lithium batteries offer enormous promise as energy sources for the dismounted soldier. Lithium systems can be categorized by the type of components (anode, electrolyte, separator, cathode); each component can be used with a variety of other components to produce a complete cell. Tables C-7 through C-9 characterize lithium battery technologies in terms of their anode structure and materials.

Table C-7 shows improvements in lithium batteries with lithium metal anode structures. To achieve the projected improvements, research will be needed in the following areas:

- Charge control in order to eliminate safety concerns
- Electrolyte and separator development to improve charge morphology
- Management of the film on lithiums surface for improved cycle life

Lithium intercalating anodes include carbon or graphite (LiC_x); tin, aluminum, and other metals; and silicon and other nonmetals are shown in Table C-8 To achieve the projected improvements, research will be needed in the following areas:

- Improved binders for improved stability of electrode
- Materials research to increase rate capability and specific energy
- Lighter weight host materials for lithium cathodes
- Improved reversibility of positive electrode materials through new preparation methods

TABLE C-8 Lithium Batteries with Lithium Intercalated Anode Structures

Present Advantages	Present Disadvantages	5 Years	10 Years
Safer than lithium metal anodes	Rate limiting electrode; no tolerance for overdischarge or overcharge	—	—
Long cycle life	Reduced power and specific energy as compared to lithium metal	Improved power and specific energy through materials improvements	Improved power and specific energy through materials improvements
	Reduced low-temperature performance	Material and electrolyte improvements	Material and electrolyte improvements
	Some voltage penalty over pure lithium	Lightweight host materials for lithium electrode	—

Lithium alloy anodes include aluminum (LixAl); ternary alloys with manganese; and other lithium alloys such as silicon alloys are shown in Table C-9. To achieve the projected improvements, research will be needed in the following areas:

- Materials research to increase rate capability and specific energy
- Charge control in order to eliminate safety concern
- Electrolyte and separator development to improve charge morphology

Lithium batteries can also be characterized with respect to electrolytes. Tables C-10 and C-11 project the developments and necessary research and development over the next ten years.

TABLE C-9 Lithium Batteries of Lithium Alloy Anode Structures

Present Advantages	Present Disadvantages	5 Years	10 Years
Increased power density as compared to lithium carbon	Reduced specific energy as compared to lithium metal	Improved specific power and specific energy through materials improvements	Improved specific power and specific energy through materials improvements
	Voltage penalty	Material and electrolyte improvements	Material and electrolyte improvements
	No tolerance of overcharge and overdischarge	—	Increased tolerance of overcharge
	Rate limiting electrode	—	—

TABLE C-10 Lithium Batteries with a Liquid Organic Electrolytes

Present Advantages	Present Disadvantages	5 Years	10 Years
Mixed organic stable at high voltages	Volatile and flammable	Material improvements to reduce flammability	Material improvements to reduce flammability
High conductivity	Requires stable separator; presently microporous polyolefins	Improved conductivity through salt research	Improved conductivity through salt research
	Some toxicity	Less toxic materials	Less toxic materials
	No tolerance to overcharge and overdischarge	—	—

Table C-10 shows improvements in lithium batteries using liquid organic electrolytes. To achieve the projected improvements, research will be necessary in:

- Materials research to identify stable nonflammable electrolytes
- Charge control in order to eliminate safety concerns
- Electrolyte and separator development to improve charge morphology
- Electrolyte salt investigation.

Table C-11 shows improvements in lithium batteries using liquid organic electrolytes. To achieve the projected improvements, research will be necessary in:

- Materials research to identify higher conductivity electrolytes
- Charge control in order to eliminate safety concerns
- Electrolyte development to improve charge morphology
- Electrolyte salt investigation
- Lithium/polymer interface reactions (a rise in cell impedance on standing and/or cycling has been observed)

TABLE C-11 Lithium Batteries with Polymer Gel Electrolytes

Present Advantages	Present Disadvantages	5 Years	10 Years
Stable at high voltages	Low conductivity	—	—
Polymer electrolyte and separator	—	Material improvements improving conductivity	Material improvements improving conductivity
Encapsulates volatile and flammable electrolytes	—	Improved conductivity through salt research	Improved conductivity through salt research
	No tolerance of overcharge and overdischarge	—	—

Finally, lithium batteries can be categorized by cathode structures and materials. Tables C-12 through C-14 summarize improvements that can be expected over the next ten years for batteries using lithium manganese dioxide spinel, lithium nickel dioxide, and lithium cobalt dioxide cathode structures. To meet expectations, efforts must be focused on materials research that increases the rate capability and cycle life of the cathode.

Other Systems

There are a variety of battery types that the committee considered inappropriate for use in dismounted soldier applications. For completeness, Table C-15 lists these battery types and the deficiencies that make them undesirable.

TABLE C-12 Lithium Batteries with Lithium Manganese Dioxide Spinel (LixMn2O4) Cathode Structures

Present Advantages	Present Disadvantages	5 Years	10 Years
Inexpensive	Poor cycle life	—	—
High specific energy	Moderate rate capability	Improved cycle life and rate through material improvements	Improved cycle life and rate through material improvements
	No tolerance to overcharge and overdischarge	—	—

TABLE C-13 Lithium Batteries with Lithium Nickel Dioxide (LixNiO 2) Cathode Structures

Present Advantages	Present Disadvantages	5 Years	10 Years
High specific energy	Poor cycle life	—	—
	Moderate rate capability	Improved cycle life and rate through material improvements	Improved cycle life and rate through material improvements
	No tolerance to overdischarge and overcharge	—	—

TABLE C-14 Lithium Batteries with Lithium Cobalt Dioxide (LixCoO2) Cathode Structures

Present Advantages	Present Disadvantages	5 Years	10 Years
High specific life	—	—	—
Long cycle life	Moderate specific power at 1 hour rate	Improved cycle life and rate through material improvements	Improved cycle life and rate through material improvements
	No tolerance of overcharge and overdischarge	—	—

TABLE C-15 Battery Systems Not Appropriate for the Dismounted Soldier

System	Deficiency
Zinc-bromine	Flowing system or noncompact, with poor volumetric and power characteristics
Nickel-iron and most lead-acid batteries	Nonsealed systems
Sodium-sulfur and lithium-iron sulfide	High temperature systems
Nickel-cadmium and silver-cadmium	Environmental problem
Metal-air	Poor power characteristics

Charging, Safety, and Testing

Major developments in electronic circuitry now permit safe and rapid charging of most battery systems; and continued advances in both capability and cost are likely. Battery systems that once were relegated to the primary (nonrechargeable) category are now sometimes used as secondary systems because inexpensive chips can monitor the batteries and regulate the charging current profile (e.g., MnO_2-Zinc). With some types of reverse-current pulse chips, recharging can be done in less than 30 minutes with lower cell temperatures (e.g., some nickel-cadmium cells). Many varieties of chargers now incorporate measurements of the state-of-charge in their control logics, and this information could be readily displayed as part of the charger design.

Lithium batteries especially must be charged very carefully. The effects of the charging current on cycle life include the formation of lithium deposits on lithium anodes and the possibility of lithium deposits on carbon anodes. Excessive charge voltages can degrade the electrolyte; when voltage exceeds the stability window of the electrolyte or electrode, it can cause a buildup of pressure and/or reactive products from electrolyte decomposition. If lithium batteries (even lithium ion batteries) are abused or improperly charged, fire or explosion may result.

Data comparing rechargeable batteries available in the general literature are unrealistic for Army use. Cycling, charging, and performance data needed by the Army should include schedules for rest time, the effects of temperature excursions, the effects of depth of discharge on performance, impedance at partial states of charge, and specific energy at different power levels. Lower voltage battery systems are inherently safer than lithium batteries, and the committee suggests that a nominal 8 V system be adopted as standard for future designs.

Necessary Technical Improvements

Major improvements (of more than 20 percent) in the performance characteristics of the battery and hybrid systems discussed in this appendix can be achieved by improvements in the following areas: processing technology; active material composition, and morphology; reinforcing components; electrolytes; and key cycle life and rate-limiting components, such as separators.

Aqueous Systems

Significant improvements in specific energy, specific power, and cycle life can be achieved by optimizing the structure and particle size of reactant materials. New low cost methods for actively preparing material will have to be developed. Candidates include xerojel and aerogel methods, using nanostructural materials, and optimizing heat treatments. Better separators will mean better electrolyte wicking and retention, which will yield longer cycle life. Better electrodes will act as structural materials, current collectors, and bipolar sheets. Improved seals will prevent gas leaks and allow for maintenance free cells. Advanced electrolyte systems, new compositions, and gelled electrolytes will contribute to better performance.

Rechargeable Lithium Cells

Research for rechargeable lithium cells should focus on the following areas:

- overcharge and discharge tolerance via cell design and charge control
- improved positive electrode materials and preparation methods for long cycle life, low cost, and environmental acceptability
- better electrolytes with greater stability, improved conductivity (both polymer and liquid), and nonflammability
- management of the Li/electrolyte interface and film
- lower cost separators

Chargers and State-of-Charge Devices

These relatively inexpensive electronic components have a major effect on battery performance and safety. The Army must keep the option for incorporating improved circuit components as they become available. Advanced charging methods can provide rapid recharging, longer cycle life, and higher performance.

FUEL CELLS

Improved fuel cell systems can extend mission times for the dismounted soldier because they can be designed to carry varying amounts of fuel for short or long missions without adding weight to the power generating part of the unit. Fuel cells differ from most other fueled systems in that system efficiency improves as the power is throttled back.

Fuel cells are generally classified according to the electrolyte and the operating temperature. For example, the solid oxide electrolyte fuel cell (SOFA) operates at 1,000°C, the molten carbonate fuel cell operates at 650° C, the phosphoric acid fuel cell (PAFC) operates at about 200°C, the proton exchange membrane fuel cell (PEMFC) at 25 to 90°C, and the direct methanol fuel cells (DMFC) operates at 25 to 90°C.

The performance level of all fuel cells that operate at temperatures above 100°C is too low for use by the dismounted soldier. Even if their performance level were higher, however, they would not be attractive because they require long starting times and have distinctive thermal signatures.

Until recently, the specific powers of fuel cells were too low to be attractive for human-portable systems. Recent advances in PEMFCs, however, have greatly improved their specific powers and significantly lowered catalyst costs. Therefore, PEMFCs should be reevaluated (Rose et al., 1994).

State of the Art

State of the art PEMFCs can operate for thousands of hours with little loss of performance and can deliver about 700 mW/cm^2 at 80°C, operating on pure hydrogen at 3 atmospheres pressure and oxygen or air at 5 atmospheres. Catalyst loadings have been reduced to about 0.3 mg platinum/cm^2 for the cathode and less than 0.1 mg platinum/cm^2 for the anode. At ambient atmospheric pressure, performance is reduced to 350 mW/cm^2 of electrode area. Unfortunately, the platinum electrocatalyst of the anode is very sensitive to certain impurities in the hydrogen fuel, including carbon monoxide and sulfur compounds.

The leading supplier of PEMFC stacks is the Ballard Company of Canada. The specific power available from the 5-kW stack is about 1,000 W/kg, and the stack is scaled down, the specific power will be reduced somewhat. Because the electrolytic conductivity of the PEMFC is a strong function of water content, the membrane must be kept in a highly hydrated state at all times. This means that heat and water management in the system are critical.

The specific power of small PEMFC stacks operating on hydrogen and air is now 50 to 100 W/kg. The rest of the system will reduce this figure significantly. For example, the Ball Aerospace "Snorkler" fuel cell system provides 100 W of power, 5 kWh of energy, and weighs 12.24 kg, corresponding to a system specific power and energy of 8.17 W/kg and 408 Wh/kg. Recent Army fuel cell project goals for small systems have been 50 W, 200 Wh, and 2 kg with specific power and energy goals of 25 W/kg and 100 Wh/kg respectively. For larger systems, current goals are 150 W, 600 Wh, 8 2.5 kg, and specific power and energy of 60 W/kg and 240 Wh/kg. These figures are for PEMFC systems that rely on oxygen from ambient air. If bottled oxygen is used, the specific power and specific energy are substantially lower.

Figure C-2 shows the estimated weight (mass as a function of energy) of H^2/PEM/air fuel cell systems, including the "Snorkler" and two future systems, one using compressed hydrogen stored at 3,000 psi and the other at 8,500 psi in an advanced wound-fiber tank. A system using hydrogen from a chemical hydride generator is also shown.

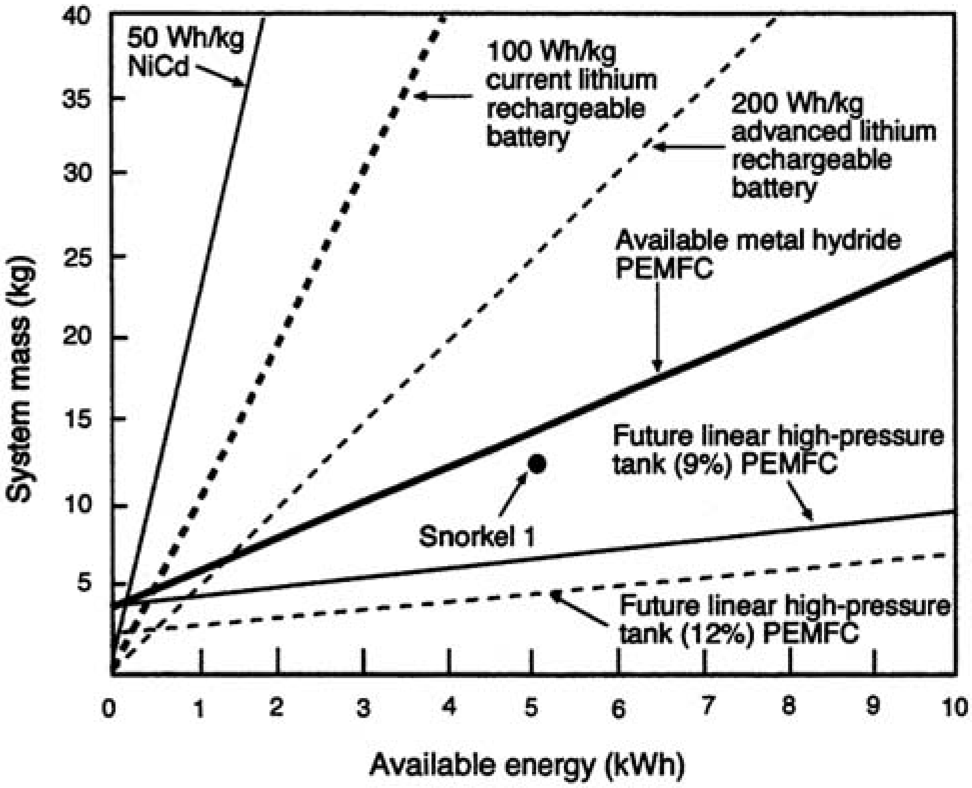


FIGURE C-2 Projected performance of 50 W hydrogen PEMFCs with a variety of fuel storage techniques.

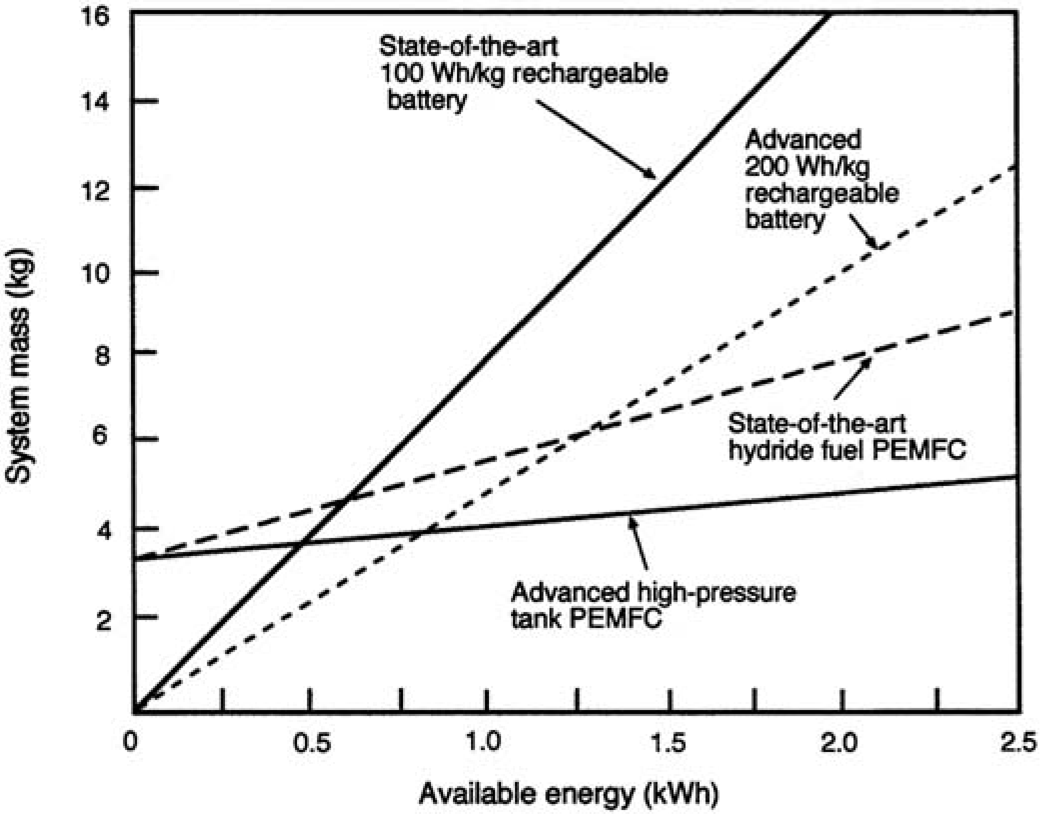


FIGURE C-3 Graph showing the crossover points for battery and fuel cell power systems asfunctions of available energy and system mass.

Figure C-3 is an expanded version of Figure C-2 that shows in more detail the crossover between the mass of battery systems and fuel cells as a function of the mission time in kWh. Fuel cells would be competitive for energy budgets greater than 1 kWh. Note that the assumed specific energy of the advanced rechargeable battery in the figure is comparable to that of current primary batteries. For advanced fuel cells, the energy storage advantage becomes apparent at approximately 0.75 kWh. For all of the figures showing system mass as a function of energy available, it is assumed that batteries can be scaled linearly to very small sizes. (In reality, off-the-shelf batteries are discrete units assembled in larger units to make up a power pack.)

On the basis of available energy, fuel cells offer a decided weight advantage when the energy demand exceeds of 1 kWh. For missions of a few hours or more, PEMFCs have an advantage over all rechargeable batteries currently available or under development. For shorter missions, the combination of relatively high specific power and reasonable specific energy make batteries more attractive.

In recent years there has been a renewed interest in DMFCs (direct methanol fuel cells) because of the possibility of avoiding the expense and technical problems involved in using hydrogen. Significant improvements in the performance of DMFCs have been made, and they now yield up to 250 mA/cm^2 of electrode area at 0.5 V/cell, with a platinum/ruthenium loading of 4 mg/cm^2, operating at 95°C, and 20 psi(g) oxygen, in laboratory tests. Endurance tests must still be performed. Additional improvements in DMFCs can be expected in the coming years.

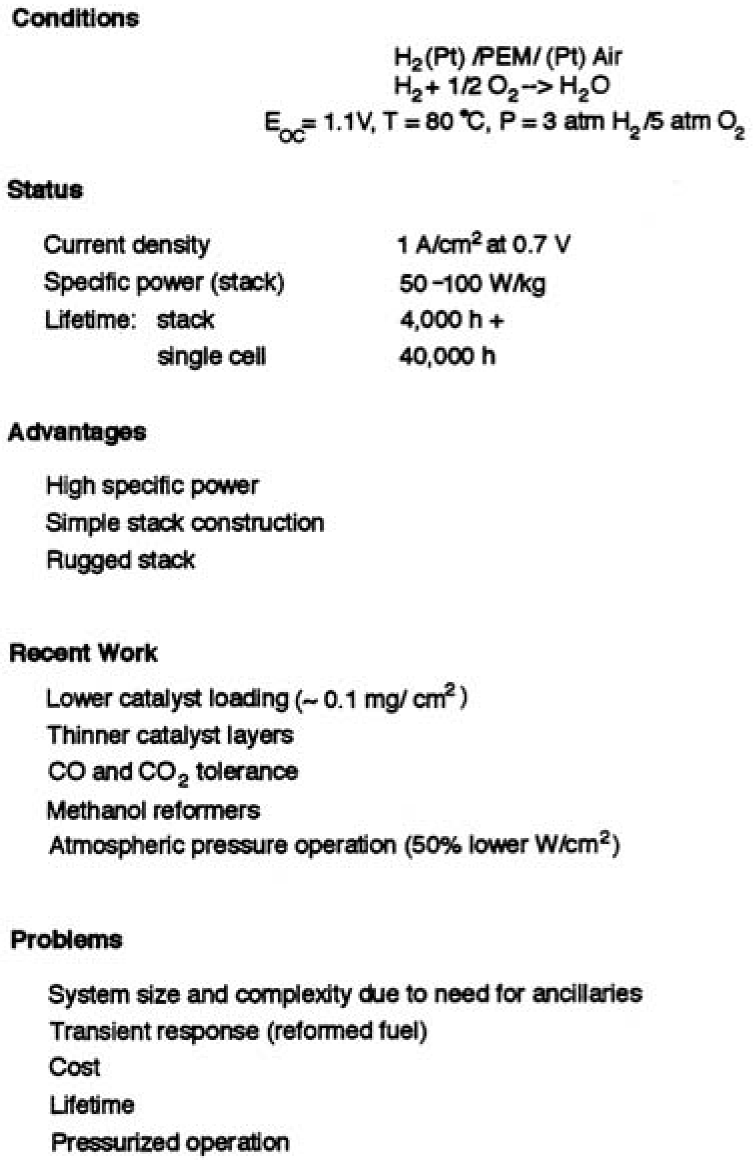
Problems

The PEMFC has been improved significantly in the past few years, but some technical and economic issues have yet to be resolved. First, the cost of a PEMFC is around \$1,000/m^2, or \$140/kW at a peak power density of 700 mW/cm^2. At lower power densities, the cost is proportionately higher. Second, simultaneous heat and water management in PEMFC systems is a significant problem for small systems because the water content of the membrane must be kept high for maximum conductivity. Therefore, thermal control must be precise in order to avoid flooding or drying out the membrane. The cost of the electrocatalyst is currently about \$10/kW at 700 mW/cm^2, which is not an overriding issue at this point.

A more significant issue is impurities. It is desirable to use hydrogen that contains small concentrations of carbon monoxide (CO), like the hydrogen that is obtained from a reformer that produces hydrogen from hydrocarbon or alcohol fuels. But platinum electrocatalyst performs well only if the CO content of the hydrogen is not significantly more than 1 ppm. Various schemes are under development to raise the tolerance level to 100 ppm.

Bipolar plates and flow distributors (also known as flow fields) in the current cell stacks are very expensive. These bipolar plate/flow distributors must be gas impermeable and electronically conductive, as well as lightweight, thin, and corrosion resistant. Corrosion resistant metals are generally too heavy and expensive to be used as bipolar plates. Carbon-filled plastics are being developed but are not yet entirely leak free.

Hydrogen storage is also a problem. In any given storage system, the hydrogen is only a few percent of the weight of the storage device, whether it is a compressed gas tank, a chemical hydride, or a metal hydride. But until the storage problem is solved, it will not be possible to realize the promise of hydrogen as a lightweight fuel. Miniature reformers that could significantly affect the utility of hydrogen as a fuel are being investigated. Their current status, however, is unclear. Figure C-4 tabulates the advantages, disadvantages, and current research focus for hydrogen PEMFCs.



Conditions

H_2 (Pt) /PEM/ (Pt) Air
$H_2 + 1/2\ O_2 \rightarrow H_2O$
$E_{OC} = 1.1$ V, T = 80 °C, P = 3 atm H_2/5 atm O_2

Status

Current density	1 A/cm^2 at 0.7 V
Specific power (stack)	50 –100 W/kg
Lifetime: stack	4,000 h +
single cell	40,000 h

Advantages

High specific power
Simple stack construction
Rugged stack

Recent Work

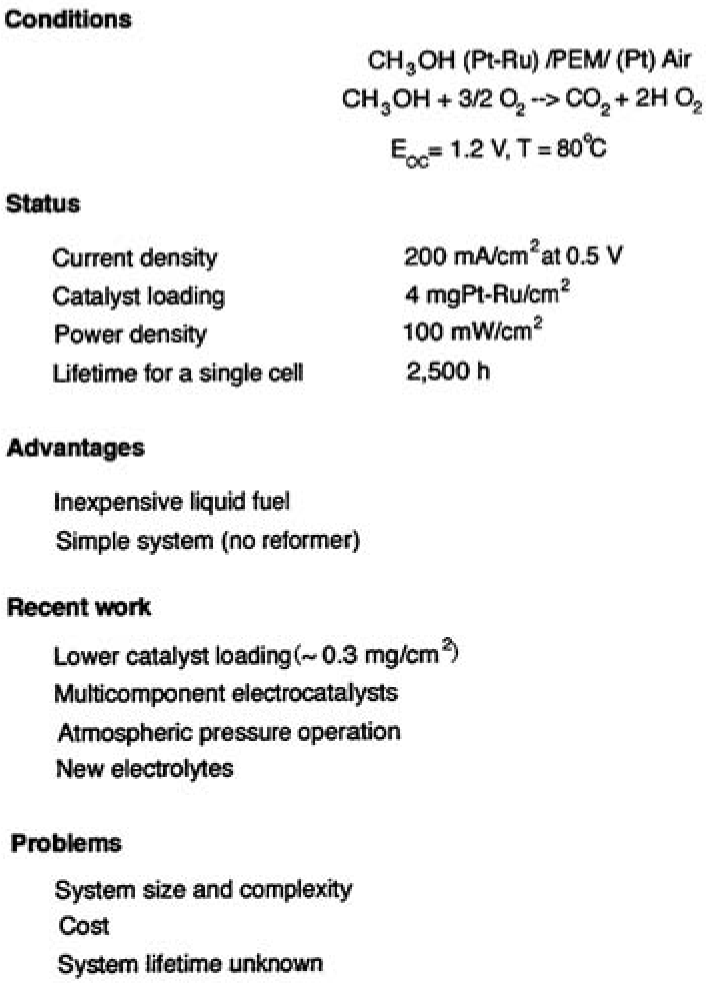
Lower catalyst loading (~ 0.1 mg/ cm^2)
Thinner catalyst layers
CO and CO_2 tolerance
Methanol reformers
Atmospheric pressure operation (50% lower W/cm^2)

Problems

System size and complexity due to need for ancillaries
Transient response (reformed fuel)
Cost
Lifetime
Pressurized operation

FIGURE C-4 State of the art of hydrogen PEMFCs.

The catalyst loadings for the DMFCs, are too high for practical use. The cost of DMFCs is about $500/kW. The efficiency of methanol utilization is low because methanol diffuses through the PEM at high rates and reacts directly at the cathode, reducing cathode performance and wasting fuel. Improved membranes and electrocatalysts are being investigated in a number of laboratories. Figure C-5 lists the state of the art and the research focus for DMFCs.



Conditions

CH_3OH (Pt-Ru) /PEM/ (Pt) Air

$CH_3OH + 3/2\ O_2 \dashrightarrow CO_2 + 2H\ O_2$

$E_{oc} = 1.2\ V, T = 80^\circ C$

Status

Current density	200 mA/cm^2 at 0.5 V
Catalyst loading	4 mgPt-Ru/cm^2
Power density	100 mW/cm^2
Lifetime for a single cell	2,500 h

Advantages

Inexpensive liquid fuel
Simple system (no reformer)

Recent work

Lower catalyst loading (~ 0.3 mg/cm^2)
Multicomponent electrocatalysts
Atmospheric pressure operation
New electrolytes

Problems

System size and complexity
Cost
System lifetime unknown

FIGURE C-5 State of the art of DMFCs.

Opportunities for Improvement

A great deal of effort has been made recently to develop PEMFCs, and significant improvements are being made every year. For small units like the ones of interest for the dismounted soldier, operating at very near atmospheric pressure (so the air feed does not need compression) will be important. Some early work in this direction looks promising. Catalyst loadings have already been reduced significantly, and several groups are working on the development of less expensive membranes and lower cost bipolar plates/flow fields. The lifetime for PEMFCs operating on pure hydrogen and air or hydrogen and oxygen are now adequate for many applications. Design modifications to meet soldier requirements will certainly yield more robust, less expensive units.

Improved electrocatalysts will be necessary for fuels other than pure hydrogen, such as methanol, for good performance with CO concentrations above 100 ppm. Improvements include more active electrocatalysts, membranes with much lower methanol permeability, and cathodes that are less sensitive to methanol. Several organizations are already working on improved membranes, but this is a difficult problem. In general, improvements in the performance and lifetimes of PEMFCs has been good, and continued progress can be expected.

In summary, the following focus areas are important to the development of fuel cells:

- developing more efficient methods of storing and/or generating hydrogen fuel
- reducing the operating pressures to near atmospheric pressure
- improving the CO tolerance of systems that use reformed fuels
- reducing the cost of bipolar plates/flow fields
- reducing system complexity
- improving water management
- reducing the cost of proton exchange membranes
- improving catalysts for DMFCs
- reducing the rate of methanol crossover
- improving system-specific power to levels greater than 100 W/kg for small (8100 W) systems at atmospheric pressure

HEAT ENGINES WITH ELECTROMECHANICAL ENERGY CONVERTERS

The energy requirements for extended missions or power-intensive activities often exceed the capacity of the dismounted soldier's batteries. The stored specific energy for the Army's best available battery today (BA 5590) is less than 0.2 kWh/kg, so this point is typically reached when missions require between 0.5 and 1.0 kWh of total energy (2.5 to 5.0 kg). For mission energy requirements above this level, fueled systems using either hydrogen or hydrocarbon-based fuels are the most attractive options. In addition to the extraordinarily high energy densities offered by these fuels, the cost for equivalent energy is several orders of magnitude below the cost of energy from batteries. The energy densities of hydrogen and common hydrocarbon-based fuels are given in Table C-16.

Options for converting the energy stored in fuels to electricity include fuel cells, thermoelectric and thermophotovoltaic sources, and heat engines with electromechanical energy converters. Of these options, conventional heat engines represent the most mature technology with unusually high converter operating efficiencies and power densities (Space Power Institute, 1992a). Potential problems associated with heat engines for the dismounted soldier include difficulty of starting, thermal and acoustic signatures, vibration, generation of toxic or hazardous combustion products, the inability to operate in all positions or to be intermittently submerged (Army Material Command, 1992). Thus, heat engines may require an intermediate energy storage mechanism to realize their full potential. An unconventional microturbine system, which is in the very early stages of development, also looks promising (Tan et al., 1997).

TABLE C-16 Specific Energies of Various Fuels

Fuel	Specific Energy(kWh/kg)
Hydrogen	33.3
Gasoline	12.2
Diesel	11.9
Methanol	5.5
Propane	12.8

A fueled power supply does not eliminate the need for a battery. It does, however, redirect the requirement to a secondary (rechargeable) battery with limited capacity that can be recharged from the fueled power supply. If battery storage is available, the heat engine can be shut off during periods of submersion, providing that reliable automatic restarting is possible.

Technical Considerations

Heat engines can be classified in a number of ways, but perhaps the distinction between internal and external combustion engines is the most appropriate discriminator for the dismounted soldier system. Internal combustion engines, such as spark-ignition and diesel engines, typically involve compressing a combustible mixture of fuel and air with a piston, igniting the mixture, which burns to produce heat, and allowing the hot gases to expand against the piston. This mechanical work can, in principle, be converted to electrical energy either by rotating or reciprocating electrical generators. In sizes appropriate for the soldier (50 to 250 W), internal combustion engines are the most mature heat engine technology (Raskovich, 1993). The impulsive nature of the thermodynamic energy conversion in internal combustion engines, however, leads to noise and vibration problems as well as difficulty in restarting.

External combustion heat engines, such as gas turbines, Stirling engines, and steam engines, are characterized by the steady-state combustion of fuel and air external to the energy conversion mechanism, which may be either rotary (turbine) or reciprocating (piston). The steady-state combustion process is generally more easily optimized, quieter, more efficient, and cleaner than the impulsive combustion process typical of internal combustion engines. Turbines are generally smoother and quieter than reciprocating engines, and the noise they do produce is typically of a higher frequency and therefore more easily dealt with. Unfortunately, certain dominant loss mechanisms for turbines (having to do with gas leakage and heat loss) do not scale well with decreasing size. Therefore, turbines in sizes below one horsepower (746 W) are rare.

Another distinction between internal and external combustion engines is their compatibility with various fuels. Present Army doctrine calls for a single battlefield fuel, such as the standard diesel fuel, JP-8. Small spark-ignition engines (such as model airplane engines), technically the most mature, typically run on methanol. Diesel engines run well only on diesel fuel. The steady-state burners of external combustion engines are more flexible in their fuel requirements. One problem common to small spark-ignition engines is imposed by their extremely low fuel flow requirements, which means orifices and fuel metering mechanisms must be extremely small. As a result, small engines are very susceptible to dirty or contaminated fuel, which may make the use of bulk fuel difficult or impossible. This sensitivity, combined with the relatively low quantities of fuel involved and the extremely diffuse consumption of the fuel, may make prepackaged fuel preferable for the dismounted soldier. Perhaps a prepackaged fuel other than JP-8 can be justified as a battery replacement rather than as a traditional bulk fuel.

Because heat engines produce mechanical power through motion, electromechanical energy converters have been the most appropriate means of conversion to electrical power. Electromechanical energy conversion is based on the fact that an electrical conductor moving through a magnetic field generates an electrical voltage. The voltage is directly proportional to the product of the magnetic flux density, the length of conductor in the field, and the velocity of the conductor relative to the field. The magnetic field can be produced either by an electromagnet or a permanent magnet.

Generally, the electromagnet is preferable because the energy conversion process can be controlled. For dismounted soldier systems, however, efficiency, low weight, and low maintenance are critical, which means generators with permanent magnet rotors will be preferable. Ideally, the generator and engine will have a common shaft and bearings to minimize weight and volume. Given appropriate electronic controls and the presence of a battery, the permanent magnet generator can also be used as a starter motor for the engine, although this may place additional demands upon the generator design. In general, for a given power output, the size and weight of the permanent magnet generator will decrease in inverse proportion to the operating speed. For microturbines, it may be necessary to develop electrostatic generators because of the small sizes involved.

The relative merits and current state of development of various heat engines for the dismounted soldier are summarized in Table C-17. Heat engines raise a common problem for military applications—the most attractive options are the least well developed. Within the power range of interest (30 to 100 W), small spark-ignition engines represent the most mature technology by virtue of the industry serving the model airplane market. However, internal combustion engines in general represent the least attractive type of engine in terms of signature, vibration, weight, operating speed, and restarting capability. The Stirling cycle engine has been the subject of substantial investigation by the Army because of its promise of multifuel operation and low signature. However present projections indicate that Stirling engines will be too heavy for the dismounted soldier system mainly because of their low effective operating pressure (Raskovich, 1993).

TABLE C-17 Internal and External Combustion Engines

Engine of Type	Level of Development	Restart	Thermal Signature	Acoustic Signature	Vibration	Weight	Appropriate Fuels [a]
Internal combustion							
Spark-ignition	high	low	high	high	high	medium	H,D,G,M,P
Diesel	medium	high	medium	high	high	high	D
External combustion							
Gas turbine	low		medium	medium	low	low	H,D,G,M,P
Stirling engine	medium	high	low	low	medium	high	H,D,G,M,P
Vapor cycle turbine	low	high	low	low	low	medium	H,D,G,M,P

[a] Key: H = hydrogen
G = gasoline
D = diesel
M = methanol
P = propane

A current project at MIT, funded by the Army Research Office (ARO) is investigating ways to apply microfabrication technology to the development of a micro gas turbine generator (Epstein et al., 1996). Based on emerging silicon-carbide microelectronics fabrication technology, this project could lead to an economical microturboalternator with high specific power. This is a high-risk project, but it could provide extremely attractive specific power and energy figures for dismounted soldier systems. A primary disadvantage is that the first generation system is envisioned to operate on hydrogen, although plans call for the development of versions that operate on JP-8. Table C-18 gives weight estimates for the engine, generator, and fuel for intermediate-and long-term technologies capable of generating 50 W. A 50 W system today would have to be assembled from commercial off-the-shelf model airplane engines and a permanent magnet generator and would operate on methanol fuel. The engine would have to be derated for silencing and would require resilient mounting for vibration control. For the long term, the microturboalternator is much more attractive.

TABLE C-18 Weight Comparison for 50-W Heat Engine Alternatives

	Weight of Base Unit			
System	Engine (g)	Generator (g)	Type of Fuel	Fuel Consumption (g/Wh)
Near Term				
Spark-ignition engine w/ permanent magnet generator	450	100	methanol or propoane	0.73
Intermediate Term				
Steam turbine w/permanent magnet generator	100	25	multifuel	0.6
Long Term				
Microturboalternator	1	included	hydrogen or	0.28
			JP-8	0.42

For the intermediate term, there is still great uncertainty. Without dedicated U.S. Department of Defense development programs, there is little incentive for the industry to develop 50-W size human-portable motor generators. Even if these generators are developed, reciprocating heat engines are likely to require heroic efforts to reduce noise and vibrations to acceptable levels.

The development of microturbines sponsored by ARO, however, does offer some attractive nearer-term options. The silicon carbide microfabrication requirement is driven by the high combustion temperatures associated with hydrogen fuel and the corresponding high turbine inlet temperatures necessary for efficient microturbine operation. The development program calls for turbines to be fabricated in silicon by 1998, which suggests the intermediate option of a silicon microturbine with a lower operating temperature driving a high-speed alternator based on rare-earth permanent magnet technology or electrostatic generator technology.

One way to achieve this power supply would be to operate the turbine as an open cycle steam turbine. Although this would require that a small amount of water or other working be carried, it would greatly reduce the operating temperature and speed of the. The weight of water is included in the fuel weight for the intermediate-term option in Table C-18.

A rough estimate of system weight (mass) for missions requiring various amounts of energy can be obtained from Figure C-6, which plots system mass as a function of available energy in kWh. In the figure, the data in Table C-18 was used to plot the weight of the engine, generator, and fuel required for 50 W of electric power as a function of mission energy requirements. The engine in the near-term option has been derated to allow for silencing, but the weight of silencing and vibration control equipment is not included.

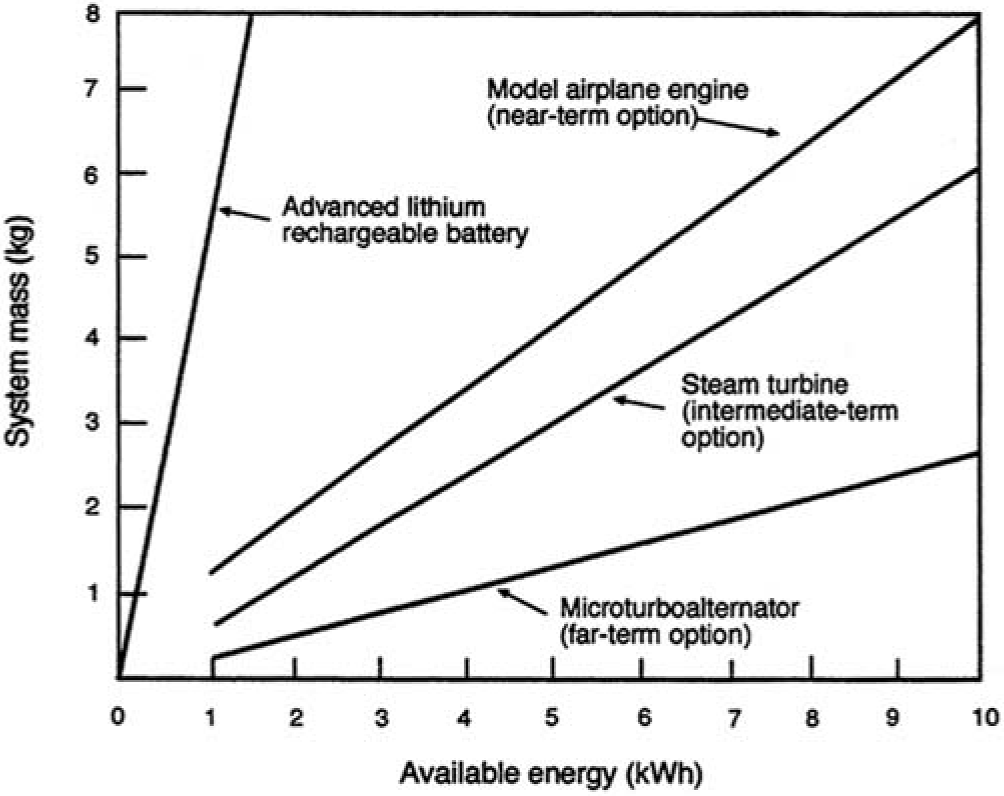


FIGURE C-6 System mass as a function of available energy.

Key Research Issues

The most promising major power systems based on rotating machinery are miniaturized turbines driven by combustion or high-pressure gases. The key research issues are:

- liquid combustion in small systems
- active noise canceling techniques
- microturbine fabrication techniques miniature electrostatic generators
- thermal signature mitigation

THERMOELECTRIC GENERATORS

The thermoelectric generator is a device that uses the Peltier effect to produce electricity from any heat source (Rowe, 1988). The efficiency of a thermoelectric generator is determined by the temperature of the heat source, the rejection temperature, and the materials that compose the thermoelectric elements. In general, thermoelectric generators are extremely reliable (they have been used for years in space), have few moving parts, and are inherently silent. They have been researched extensively for use in space.

Technical Aspects

At present, the maximum efficiency attainable from thermoelectrics is on the order of 8 to 9 percent in a laboratory device, but the efficiency is usually less than 5 percent. The best converter materials are alloys of materials like bismuth and tellurium, which are expensive and difficult to fabricate. The Defense Advanced Research Projects Agency (DARPA) has recently initiated a program to develop advanced thermoelectric materials for both power and cooling. This program may eventually enable the construction of power systems with efficiency greater than 10 percent, which would make them competitive with some of the other systems outlined in this report.

Teledyne Brown Engineering manufactures and markets large thermoelectric units for use in remote areas. The maximum power levels for these units are on the order of 100 W. The units are multifuel-capable and highly weather resistant, traits that would be of considerable interest to the military. In the 1960s, the Army experimented with thermoelectric units for battlefield use. The units were less than 5 percent efficient and very heavy. As a consequence, they did not become part of the standard inventory. More recently, the Marine Corps has funded a design study for a 500-W unit projected to weigh 20 kg and have an efficiency on the order of 9 percent (Bass et al., 1994). The specific power of this unit is on the order of 25 W/kg for the converter alone. Because this is a converter, specific power is determined by the basic weight of the assembly plus the weight of the fuel that would be needed for a mission. Continuing research at the Jet Propulsion Laboratory indicates that converters with efficiencies of greater than ten percent are possible (Halpern, 1997). Figure C-7, which shows the system mass as a function of mission energy, assumes that this device could be realized.

Key Research Issues

Thermoelectrics is a mature technology that has been used for numerous space applications for power, as well as for an enormous array of civil and military applications for cooling. Like other mature technologies, thermoelectronics tend to improve incrementally. The following are key research issues:

- development of materials with high "figure of merit" for power applications
- development of low cost fabrication techniques
- external combustion and recuperation in small systems
- building prototype power systems

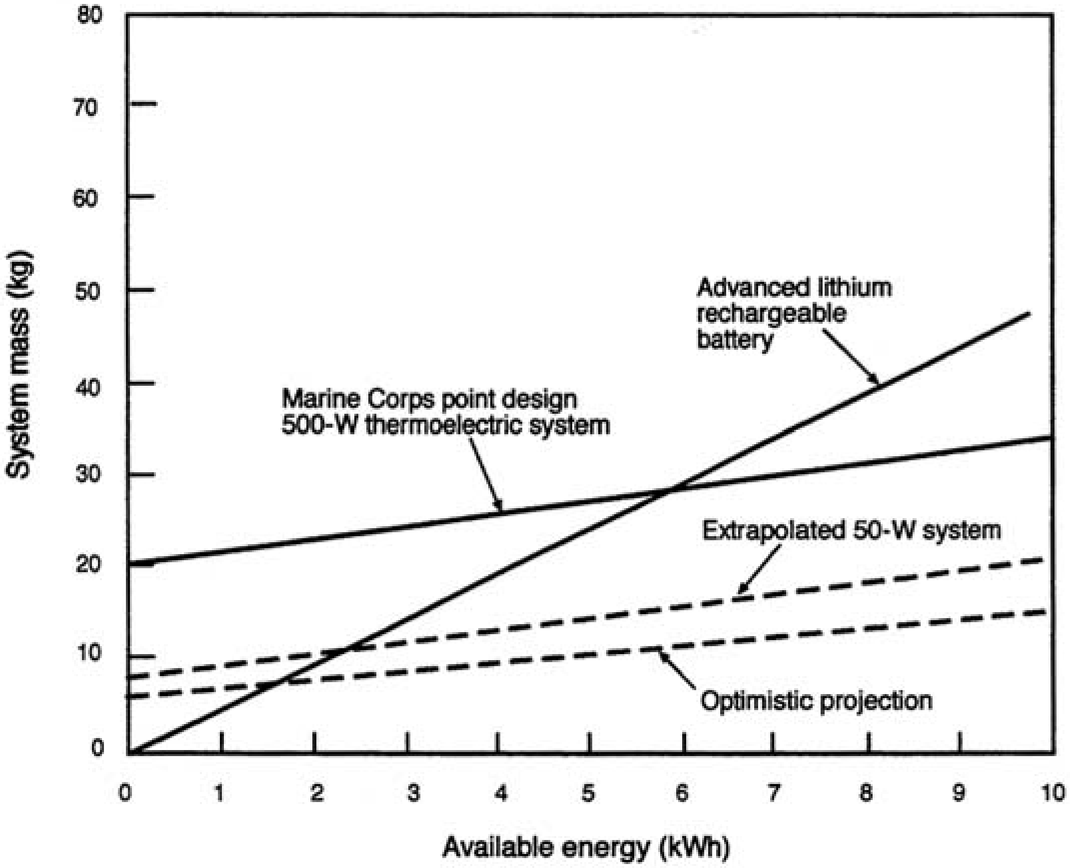


FIGURE C-7 Available energy as a function of power system mass for a thermoelectric power generator fueled by battlefield fuel.

ALKALI-METAL THERMAL-TO-ELECTRIC CONVERTER

The "sodium heat engine," or alkali-metal thermal-to-electric converter (AMTEC), is capable of converting thermal energy from any heat source to electricity with efficiency estimates as high as 35 percent (Space Power Institute, 1990). This technology has been extensively investigated in the past decade, and much progress has been made in materials technology and in understanding the basic physics of single cells. Extensive efforts have been made worldwide to reduce the technology to practice. In the civilian sector, applications such as automotive, self-powered home gas appliances, and space power have been explored. The most interest at present is in applications for deep space probes, where the heat source is nuclear. Because the fundamental physics of the converter is independent of the heat source and because modest laboratory efficiencies have been obtained, AMTEC should be a good candidate for Army applications in the 50 to 500-W range.

Technical Description

AMTEC consists of a liquid sodium loop with high and low temperature sections separated by an ion permeable membrane (Figure C-8). At the high-end, there is a pressure gradient across the membrane, which causes sodium ions to flow through the membrane but blocks sodium atoms. If electrodes are placed across the membrane, ions passing through the membrane create an electric potential that can be used to do useful work. Because the liquid associated with the converter is a metal, electromagnetic pumps or a "wick" can be used to return the liquid from the cold to the hot side, minimizing the number of moving parts. It is estimated that an AMTEC may be configured to be as high as 500 W/kg in specific power although no experimental units have demonstrated power densities approaching this value (Ivanenok and Hunt, 1994). Experimental units have been operated in a laboratory environment for thousands of hours demonstrating the potential for long life.

The basic device is adaptable to any heat source capable of maintaining a 500 to 700 K (degrees Kelvin) temperature differential across the converter section of the unit. The estimated cost per kW will be on the order of $0.30 to 0.50/W. To date, single AMTEC cells have operated in excess of 14,000 hours. There are no reported data on the operating history of cells in parallel or series arrays, which would be necessary to produce an efficient power supply. The unique construction of an AMTEC cell presents serious problems to the development of efficient series and parallel arrays.

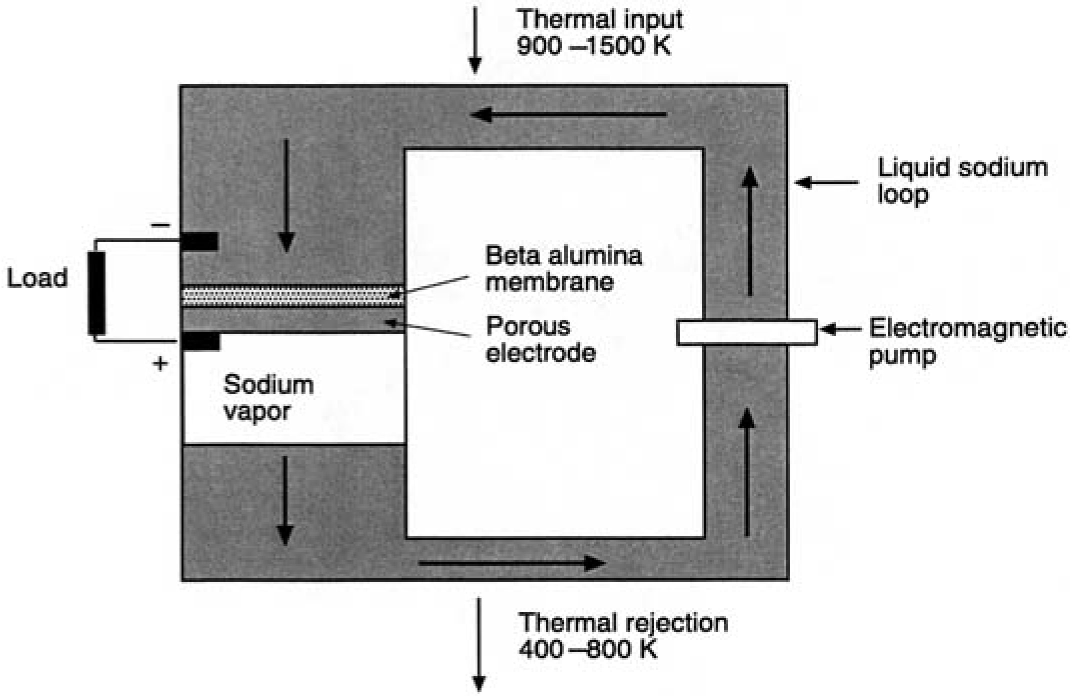


FIGURE C-8 Schematic drawing of an alkali-metal thermal-to-electrical converter (AMTEC).

Point designs, which would allow estimates of system mass, have not been built. Technology projections must, therefore, be based on analytical studies, and on the fact that AMTEC scales linearly to small sizes. Figure C-9 illustrates system mass as a function of mission duration in kWh based on published estimates of efficiency and specific power (Ivanenok et al., 1993, Ivanenok and Hunt, 1994).

AMTEC, like all fueled systems, has the problem of rejecting waste thermal energy at a relatively high temperature. This poses a serious design constraint or limits the system's utility to areas where there is no concern about thermal signature.

Key Research Issues

At the single-cell level, AMTEC converters are well understood. The primary technical and research issues to be resolved are:

- long term materials degradation and poisoning of the alkali-metal loop
- techniques for effectively and efficiently making parallel and series arrays that minimize heat loss
- efficient external liquid combustion and recuperation in small systems
- system demonstrators

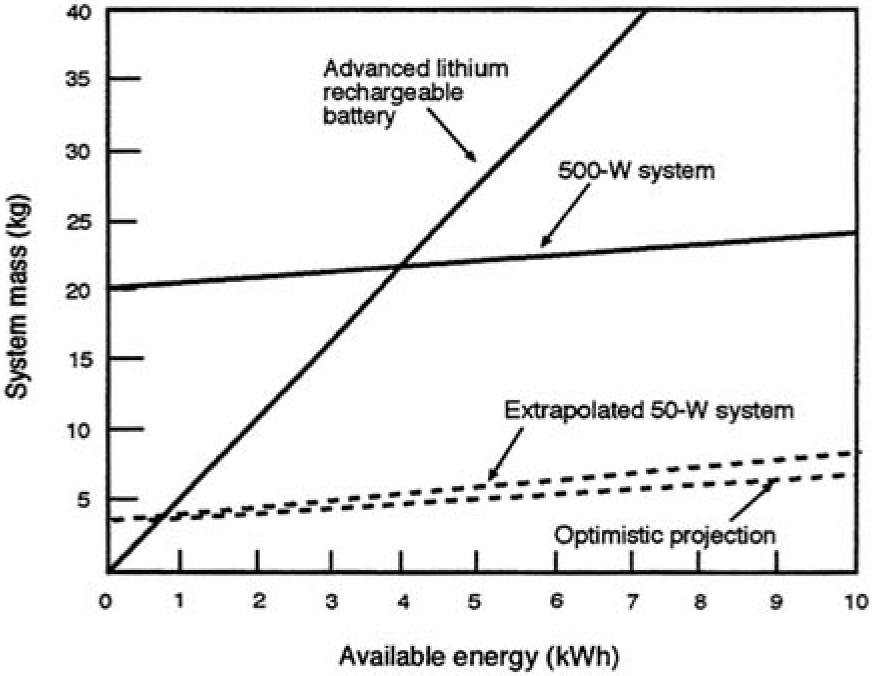


FIGURE C-9 Estimated performance of an AMTEC system.

NUCLEAR ENERGY POWER SOURCES

Power sources based on nuclear energy are capable of more than 1,000 times the specific energy of power sources based on chemical bonds (see Figure C-1) (Space Power Institute, 1992c). Releasing nuclear energy in a controlled way, however, is extremely difficult. Nuclear energy sources are included in this study for completeness, although the problems of using nuclear materials on a battlefield are formidable and could be overcome only by a concerted and expensive program. Nuclear power sources could extend the autonomy of the soldier to months and years instead of hours.

The most applicable nuclear energy sources that might be exploited by the Army are nuclear isotopes (NTSE, 1992). Isotopes have the following desirable attributes:

- They possess enormous specific energy.
- Systems utilizing isotopes can be made with a wide range of specific powers.
- Isotopes suitable for power applications are by-products of nuclear reactor operations.
- Isotope power systems are highly developed and reliable.
- Isotope power systems offer a wide range of options for energy conversion.

The fundamental properties of isotopes will severely restrict their use, however. The most obvious limitations are:

- Isotope power systems cannot be turned on and off. Once activated, the isotope begins to decay while still in the reactor.
- Massive shielding is required for some isotope fuels.
- Environmental/health issues are associated with both the manufacture and use of isotope systems.
- Nuclear-powered systems in general have a poor public image.
- The most desirable isotopes are expensive.

For the reasons listed above, power systems based on nuclear isotopes have been niche technologies, confined primarily to space probes, underwater power systems, and use in remote terrestrial locations. Nevertheless, the list of potential applications that could benefit by the use of isotope systems is long.

Generic Radioisotope Power Systems

Current space systems employ the general-purpose heat source-radioisotope thermal generator (GPHS-RTG) and the next generation, the modified, or MOD-RTG. The GPHS-RTG, as flight hardware, has a nominal efficiency of 6.8 percent and a specific power of 5.18 W/kg (electric). MOD-RTG should have an efficiency of 7 to 9 percent and a specific power of 7.7 W/kg (electric). Mini-RTGs using the same technology have been designed for lunar and Martian probes with comparable efficiencies. For terrestrial use, the specific power is less important, and these units tend to be more massive, due to the use of ^{90}Sr and ^{60}Co. The mass increase is usually in shielding or in pressure vessels if the unit is used for deep sea submergence. The conversion efficiency is in the range of 5 to 9 percent, depending on the thermoelectric materials used. All currently operating RTGs are powered by thermoelectric converters.

Several small units designed for probes of the lunar and Martian surfaces may be of interest as terrestrial power sources. The innovative designs of these RTGs may be more mass and volume efficient because fuel does not have to be encapsulated to survive inadvertent reentry. Other innovations in insulation, such as the innovations proposed for the MOD-RTG, can also be used for mass savings. Miniature heat engines, such as Stirling engines, AMTEC, and thermophotovoltaic devices, some with efficiencies as high as 30 percent, could be coupled with RTGs with the possibility of repair and replacement. High efficiency reduces the quantity of radio isotopic materials required as the heat source.

The conversion process from nuclear to thermal energy is inherently efficient; therefore, the major advances will be in the thermal-to-electric conversion process. The most promising conversion technologies are thermoelectrics; thermodynamic cycles, such as Stirling, Brayton, and Rankine; thermionics; thermophotovoltaics; and AMTEC. All of these technologies have progressed to laboratory scale demonstrations, and some are being tested in system demonstrations. Power conditioning can be summarized as highly efficient, with power densities on the order of 2 kW/kg and efficiencies above 90 percent. With most of the low voltage, high current conversion requirements employing thermophotovoltaic, thermoelectric, and thermionic converters, such as series-parallel arrangements for small units, the output voltage and current can be tailored for a specified load. Mechanisms with rotating machinery must include alternator designs that fit specific loads; several mechanisms, such as the linear alternator, have been investigated.

Major programs are under way to develop new thermoelectric materials and improve existing ones through judicious materials engineering. The key issues are increasing thermal-to-electric conversion efficiency by selection of materials and by using dispersions to control thermal conductivity. For thermionic converters, both fuel encapsulation to prevent element swelling and high temperature emitters are vital to reliable power systems. For thermophotovoltaics, the key issues are the development of "low-bandgap" cells with acceptable efficiency; the current state of the art is approximately 10 to 20 percent. Dynamic machines and technologies, such as AMTEC, have materials problems that are not inherent in the conversion process but that require engineering of some components for durable long lasting systems. These components include seals, membranes, bearings, and insulators.

Safety and environmental considerations are inherent in the design of all power systems. Both concerns are subject to U.S. Department of Energy procedures, as well as state and local requirements. In fact, satisfying the myriad requirements has become a major cost factor. The nuclear industry associated with small power sources has an impeccable record of addressing environmental and safety issues through extensive testing programs. Disposal is not a problem for deep space and planetary probes. But if terrestrial use increases significantly, disposal will become a critical issue that must be addressed in advance.

The selected fuel must not pose a threat to the environment or to human health. Unfortunately, the most desirable fuels are not available in quantities necessary for power applications. Hence, fuel type is also a critical issue. For terrestrial applications to date, the fuels have tended to be ^{60}Co and ^{90}Sr, both of which were available from reprocessed nuclear reactor fuels. Some fuel-grade materials are in storage, but they are decaying rapidly and will be of limited use in another 10 years. Because the United States does not produce suitable quantities of fuel, they must be purchased from countries that routinely reprocess nuclear materials or specialize in isotope production. The United States recently purchased ^{238}Pu from Russia to meet NASA's projected needs. China, Canada, Japan, and France are other potential sources.

Many potential terrestrial applications for radiothermal generator technology are not being pursued, primarily because of public perception, the cost of materials, and environmental and safety issues. Most of the nuclear systems used to date have used thermoelectric converters. Conversion efficiency is expected to improve by a factor of two to five in the near future for converters on thermodynamic cycles and for technologies like AMTEC and thermophotovoltaics. But even if the use of nuclear materials were acceptable, the isotope manufacturing industry in this country is bordering on collapse. Before radiothermal generators can be widely used, the public perception of nuclear systems will have to change significantly.

Key Research Issues

The enormous specific energy of nuclear fuels makes them very attractive candidates for Army and civilian use. But the practicality of using nuclear fuels is low because of concerns about safety, environmental impact, cost, fuel infrastructure, public image, and the poor shelf-life of more powerful isotopes. Indeed, an isotope that could be used in a power system begins to generate energy the moment it is made in a reactor and cannot be turned off. Therefore, the key issues deal with system studies rather than fundamental research. The Army should:

- Conduct system studies to characterize nuclear systems within an Army context.
- For extremely low power requirements, explore miniature beta-voltaic nuclear powered systems that could be integrated into an electronic integrated circuit chip.

HUMAN-POWERED SYSTEMS

With sophisticated energy management and low power electronics, the energy requirements of the dismounted soldier could be reduced to a level at which the soldier could individually generate a substantial portion of the electrical energy required for a mission. It would only be necessary to convert some of the energy expended by the soldier during everyday activities to electricity.

The human body stores an enormous amount of energy. The average body is approximately 15 percent fat and represents a stored energy greater than 11,000 Wh. The average person consumes between 2,000 and 3,000 calories per day, which is, in more familiar units, approximately 2,200 Wh to 3,300 Wh. It can take 30 minutes to consume food with this energy content, so the charge rate is about 7 kW for 3,000 calories. Clearly the amount of energy consumed by an individual is sufficient to provide power for electronic devices if a suitable method can be found of converting even a small fraction of that energy to electricity.

Technical Discussion

The amount of power associated with physical activity has been estimated by Morton (1952). Table C-19 lists power levels associated with physical activity that would be of interest to the dismounted soldier.

TABLE C-19 Power Levels Required for Some Common Human Activities

Activity	Power(W)
Sleeping	81
Standing at ease	128
Walking	163
Walking briskly	407
Long distance running	1,048
Sprinting	1,630

TABLE C-20 Estimates of the Maximum Power Available for Conversion to Electricity from Several Body Sources

Source	Maximum Power, Available(W)	Maximum Estimated Conversion efficiency
Body heat	116	~3% (assuming total capture)
Breath	1.0	40% (based on turbine efficiency)
Blood pressure	0.9	about 2%
Upper limb motion	24–60	83%
Walking (heel strike)	67	piezoelectric converter~7% generator ~50%

Source: Starner, 1996.

In a recent article, Starner (1996) described several potential sources of energy associated with the human body that might be tapped for conversion to electricity (Table C-20).

Limb motion and the heel strike associated with walking and running are potential sources of power as long as the requirements are for levels of a few Watts. Because physical activity is inherently intermittent, a storage mechanism will be necessary. Rechargeable batteries, electrochemical capacitors, pneumatics, springs, and flywheels are candidates. Rechargeable batteries and electrochemical capacitors are discussed elsewhere in this chapter. The storage density using spring metals is on the order of 0.4 to 1.0 joules/gram, making them an attractive candidate. Conversion to electricity will require a generator of some sort. Wind-up shavers, radios, and flashlights are currently available on the civil market. Although the idea of human-powered systems is intriguing, it is impossible to estimate system performance in units like Wh/kg and W/kg at this time.

Key Research Issues

The field of human-powered systems is considered new and innovative, but human power has been used for electrical and mechanical systems for decades. The hand-cranked portable generator currently used by Army special operations forces falls into this category. It is possible to generate up to 100 W in this fashion. But devices of this type are not passive, and using them effectively immobilizes the individual while power is being generated. Another example is the small "flashlight" that is energized by squeezing a lever. For purely mechanical conversion, the Apollo astronauts took with them to the moon a rotary shaver that employed a small flywheel energy store activated by pulling a cord. Except for the few references already cited, no research on exploiting the energy associated with body motion and converting it to electricity is under way. Research in the following areas could affect human-powered electrical systems:

- development of efficient lightweight intermediate storage units
- analysis of the human motion in routine tasks and coupling unobtrusive converters to this motion
- development of laboratory prototypes with small electromechanical and piezoelectric converters

PHOTOVOLTAIC TECHNOLOGY

Photovoltaics technology has been developed largely for use in space. Therefore, the following discussion relies heavily on data from that sector. All of the material for this section came from the Institute of Electrical and Electronics Engineers (IEEE) Photovoltaic Specialists conferences (IEEE, 1996). At the earth's surface, the power incident from the sun is on the order of 1 kW/m^2 of surface. Conversion at modest efficiency should result in a major energy source that is "there for the taking." Successful harvesting of solar energy depends on the development of affordable photovoltaic cell technology. In general, the cost in terms of dollars per Watt have been too high for large-scale commercial exploitation, even though the U.S. Department of Energy has funded large demonstration projects capable of producing megawatts of electrical power. Solar photovoltaics is also limited because systems can produce power only during daylight hours and on clear days. Furthermore, for optimal power production, the unit must "track" the sun. The Army currently uses solar battery chargers for desert operations. These arrays can be folded and produce enough power to charge several batteries. Several thousand units were used in Operation Desert Storm.

Many domestic and foreign suppliers of photovoltaic cells have been in business for more than 30 years. They have already developed and implemented the process controls and inspections required for cells for general usage. These suppliers are reliable and they supply industry and government organizations around the world.

Currently most photovoltaic cells are used on commercial satellites, more than 400 of which are planned for the next five years. About 75 percent of production is devoted to gallium arsenide (GaAs) cells; silicon (Si) cells account for about 20 percent. A small fraction of production is devoted to higher efficiency multijunction cells and other cell types based on Group III, IV, and V elements. Three satellite classes comprise the marketplace: geostationary earth orbit communication and weather satellites, midorbit constellations (such as Iridium by Motorola, Odyssey by TRW, and Globalstar by Loral), and low earth orbit satellites (such as the space station and earth observation and earth science satellites). Divided by specific customers, the commercial marketplace is booming. The U.S. federal government market share is small to moderate, except for the space station, whose production run is already over. Cell production capacity amounts to approximately 300 to 500 kW annually, for total sales of roughly $80 to $150 million. These specialty cells cost from $266 to $300/W, far too much for general use. Table C-21 summarizes the potential of photovoltaics as a source of energy.

Cells

Silicon

The silicon solar cell, which once was ubiquitous, is now a minor part (about 20 percent) of the market. In polycrystalline form, silicon solar cells have an efficiency of up to 15 percent and can be produced in virtually any rectangular size up to 36 to 50 cm^2. In single-crystal form, their efficiency can be as high as 25 percent. Silicon solar cells come in many configurations with back surface fields (BSFs), back surface reflectors (BSRs), textured surfaces, or multilayer antireflection coatings, and in various base resistivities. For space-rated systems, the price of silicon cells is approximately $100/W, depending on the design. The more features, the higher the price. Civil sector prices for polycrystalline silicon arrays are on the order of $5/W.

TABLE C-21 Summary of Photovoltaic Technology

Cell Technology	Commercial Availability	Cost	Power Density (W/m^2)	Efficiency (%)
Amorphous silicon	limited	?	50–70	5–10
Polycrystalline silicon	yes	low	130–140	14–15
Single-crystal silicon	limited	high	200	24–26
Gallium arsenide	limited	high	200	17–18
Indium phosphide	no	high	200	17–18
Copper indium diselinide	no	high	130	15–17
Multibandgap	limited	high	250	25–30
Concentrator array	limited	high	250	30

Gallium Arsenide

The gallium arsenide/germanium (GaAs/Ge) solar cell has become the cell of choice in space because of its higher efficiency and its increased radiation tolerance. GaAs/Ge cells are about 17 to 18 percent efficient and are made in sizes up to about 24 cm^2. They are fabricated by growing layers of GaAs onto rugged Ge substrates by chemical vapor deposition. These cells overcome the inherent fragility of GaAs, as well as the very high cost of GaAs single-crystals. The Ge substrate is inexpensive and very strong but is not part of the photovoltaic device in this design. The price of GaAs/Ge cells is approximately $300 to 400/W. There is no widespread commercial market for these cells. However, prices for terrestrial markets are much lower than for space-rated systems.

Indium Phosphide Cells

Indium phosphide (InP) solar cells are attractive for use in space because of their extreme radiation resistance. The efficiency of InP single-crystal solar cells is about the same as GaAs cells: about 17 percent, with sizes of about 4 to 8 cm^2. InP cells are essentially unaffected by electron radiation and show only slight effects from proton radiation. Results of recent tests show that InP solar cells will lose about 5 percent of their power after 15 years in geostationary orbit. Furthermore, this damage can easily be annealed at temperatures of about 100°C. The main drawback of single-crystal InP solar cells is their cost, at present about $500 to $1,000/W, mostly because of the cost of the single-crystal substrates. Several researchers have tried to deposit InP solar cells onto Si substrates with modest success. Efficiencies of about 12 percent have been achieved to date. There is currently no terrestrial commercial market for these cells.

Multibandgap Solar Cells

Multibandgap (MBG) solar cells are composed of individual solar cells with appropriate bandgaps formed on top of one another for maximum utilization of the solar spectrum. Two- and three-junction devices are being studied. One example is GaAs/Ge cells, in which both the GaAs and Ge are active devices connected with tunnel junctions. Another is $GaInP_2$/GaAs/Ge, a triple-junction cell. Most of the Group III, IV, and V elements are being investigated for use in MBG cells. Present goals of the technology are to achieve efficiencies higher than 24 percent for dual-junction cells and higher than 26 percent for triple-junction devices. So far, these values have been essentially achieved in practice (23.7 percent for $GaInP_2$/GaAs, and 25.7 percent for $GaInP_2$/GaAs/Ge in 4 cm^2 areas), although production averages may be 1 to 2 percent lower at this time. The cost of dual-junction MBG cells is presently $400 to 500/W. Present capacity for dual-junction cells is 100 to 200 kW per year. There is no substantial commercial market for these cells because of their high cost.

Thin-Film Cells

Thin-film solar cells have always been attractive as a low cost alternative to single-crystal cells. Unfortunately, their efficiency has always been substantially lower than conventional Si or GaAs cells. The two thin-film cells that have been proposed most frequently are amorphous Si and copper indium diselenide (CIS). Amorphous Si cells have efficiencies of about 5 to 10 percent, are deposited onto either metallic or polymeric substrates, and may have multiple junctions. They are subject to photon degradation and lose about 20 percent of their output when illuminated. Thin-film cells can be manufactured in virtually any size up to several square feet, with cells interconnected as part of the processing. CIS cells have efficiencies of about 15 to 17 percent and are not subject to photon degradation. Neither cell type is available in production quantities.

Arrays

Planar Arrays

Planar arrays, which make up more than 99 percent of the market, can be body mounted or paddle mounted. Both flexible arrays (for the space station) and rigid arrays (for communications satellites) are in regular production. Specific performance values depend on the exact application; the space station array has specific mass of about 55 to 60 W/kg with an overall efficiency of roughly 75 to 80 percent of the cell average efficiency (accounting for mismatch losses, area losses for interconnection and spacing, and wiring losses). Rigid arrays have specific powers of about 25 to 30 W/kg, with similar efficiencies. The costs of arrays are system dependent, with cell costs being up to one-third of the total. Cells are interconnected by welding or soldering metallic tabs in a series/parallel arrangement to ensure reliability. The reliability of solar arrays in space has been excellent, exceeding 99 percent.

Concentrator Arrays

A recent attempt to reduce the cost of solar arrays has been the development of the linear Fresnel-lens concentrator array. In this configuration, a lens concentrates sunlight (about 15 times) onto a row of solar cells. The small area solar cells produce a higher efficiency because of the brighter light and smaller area—up to 25 percent for a single-junction GaAs cell or 30 percent for an MBG cell. Because the optics are less costly than for solar cells, the costs of the array are lower—as little as half the cost of a planar array. Concentrator arrays do require increased pointing accuracy (1 to 2 degrees compared to 15 degrees for planar arrays).

Key Research Issues

Photovoltaics, like many of the technologies discussed in this report, are mature in many applications and have been in the commercial domain for many years. Currently, the specialized space applications are able to afford cells that are more efficient than those widely available on a commercial basis. The cost of these specialized cells is orders of magnitude greater than the cost of cells that are commercially available generally. Photovoltaics are already being used by the Army.

Reductions in power requirements made possible by advances in low power electronics (described in Chapter 4) could make personal photovoltaic chargers in sunny climates a practical alternative to fueled systems. The following areas should be investigated:

- bandgap-tailored photovoltaics that could function with both artificial light sources and the solar spectrum
- manufacturing technology to reduce the cost of photovoltaic cells
- innovative system demonstrators

THERMOPHOTOVOLTAICS

Thermophotovoltaics (TPV) is the technology for converting energy from an incandescent object (from any heat source) to electricity (Brenner et al., 1995). TPV technology shows great promise for the development of portable power sources for the dismounted soldier. Figure C-10 illustrates the concept.

Recent advances in TPV technology suggest that power systems for the dismounted soldier could provide anywhere from a few Watts of power to more than 500 W. Improvements in photovoltaics and emitters, in terms of reliability, size, weight, and energy efficiency, will translate directly into increased capability and, perhaps, lower cost. TPV is a multidisciplinary field. For example, solid-state converters must be combined with a radiant element, which is heated from a fossil-fueled combustion source. Recovering the energy remaining in combustion gases is vital for efficiency.

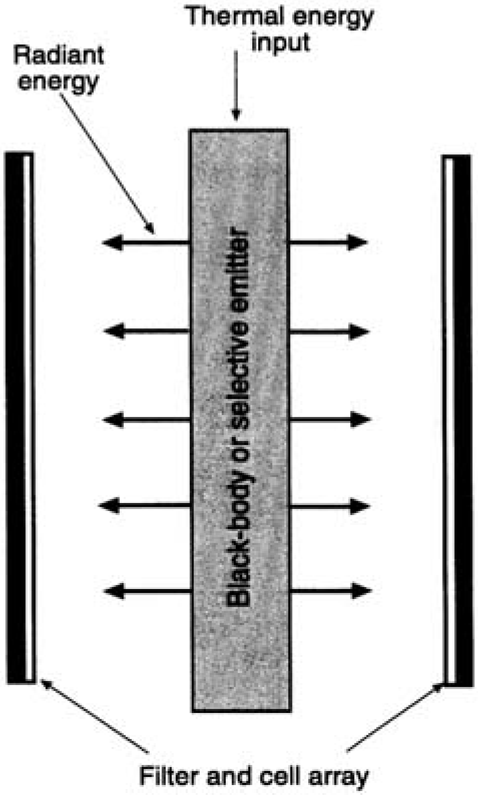


FIGURE C-10 Schematic drawing illustrating the principles of thermophotovoltaic (TPV) power systems.

The ultimate utility of TPVs for the Army may depend less on the fundamentals of the devices themselves than on other factors, such as whether a device can be mass produced from affordable materials, whether a device can be made robust and reliable enough to function in a hostile environment, whether it can be engineered into a package with minimal signature, and whether it will enhance the capability of soldiers in the field.

State of the Art

Many organizations have become interested in TPV technology, and a wide range of individual components have been demonstrated on a laboratory scale. These components appear to be ready for rapid development once applications have been identified. Examples include photovoltaic cells with conversion efficiency of greater than 20 percent, black-body-like emitters, selective emitters that emit greater than 50 percent of the energy in a narrow band, burners with combustion efficiency greater than 90 percent, cavities with losses just now being defined, filters with efficiency greater than 80 percent, coolant schemes that are readily adaptable to cooling photovoltaic cells, and designs for high temperature recuperators (Space Power Institute, 1996). So far, only a few of these components have been assembled into laboratory systems that indicate feasibility but provide only inefficient demonstrators. The most prominent example is the Midnight Sun™ device from JX Crystals.

Several programs have been funded to increase power output to more than 500 W. Most of these are funded by the DARPA, ARO, and the Army Research Laboratory; laboratory demonstrations are expected within one year. The emphasis to date has been on demonstrating capability, materials, and processes for laboratory devices. Packaging is only now being addressed and should clarify many of the obstacles to fielding devices. Very little attention has been paid to demonstrating full systems or to establishing engineering parameters, such as figures-of-merit, performance specifications for each component, or the range of parameters for each component, although an infrastructure is emerging. Major potential applications in the military are auxiliary power units (APUs), battery chargers, and direct battery replacement.

TPV can potentially compete in the civilian markets in cogeneration schemes with gas furnaces, gas water heaters, and as stand-alone auxiliary power for pleasure craft. The technology to build systems with efficiencies greater than 10 percent is already available. The most optimistic projections for efficiency are on the order of 30 percent. Until more emphasis is placed on recuperation, it will not be possible to determine the specific power; however, specific powers greater than 100 W/kg do appear to be reasonable. Useful devices can be built with existing technology, but research to optimize and improve performance can be pursued in two areas, materials technologies, and manufacturing and packaging technologies.

A host of materials are used in TPV technology, especially in the radiating element. Both black-body and selective radiators are possible. In general, the choice of material has been at the discretion of the particular investigator. Little is known about the degradation (if any) that will occur when radiators are operated at high temperature for long periods of time. Strength, chemical composition, and vapor pressures at the operating temperature must still be studied.

Efficient reflective filters are also necessary for efficient TPV systems. Optical recuperation and thermal recuperation are necessary. Placement of the filter is critical for efficient optical recuperation; filters will be subjected to the total radiant thermal flux and must be able to withstand high temperatures. Highly efficient, cost effective filters are vital and should be researched in depth.

For TPV power systems to be affordable, the cost of photovoltaic cells must be reduced by orders of magnitude. The requisite manufacturing technology will be put in place only if there is an adequate market. To date, the best cell technology has not been identified; GaSb, In GaAs, and Si are all contenders. The difficulty with Si is the large bandgap, which necessitates high temperatures in the TPV unit. These temperatures place unique demands on recuperators. Cells based on other materials should be researched to provide the data for cost / efficiency trade-off studies for specific applications.

Recuperators are reasonably well established for temperatures compatible with high temperature metals and alloys. Considerable work needs to be done to establish the technologies for temperatures greater than 1,700 K. Because there are no complete systems, little is known about subsystem interactions. Models that can accurately predict system performance and subsystem interactions will have to be developed. Issues like service life can only be discussed in the framework of a specific application and system concept. At this stage, there are no specific devices that can be evaluated in the context of the battlefield environment.

For a given illumination intensity, the power output scales linearly with the area of the photovoltaic array. Energy scaling is related solely to system efficiency. Simple scaling estimates can be derived from the response of the photovoltaic cells and assumptions about efficiency. The total mass of the system is quickly dominated by the fuel mass. The minimal mass of the system is determined by items such as fuel tank, recuperator, cell array and structure, coolant scheme, and controls necessary to make the device user friendly. It is impossible to determine how these components effect scaling until some complete systems are built. Once fuel mass becomes dominant, scaling is linear in fuel mass. Size and capability are only meaningful in the framework of an application. As systems emerge, detailed scaling can be established. Figure C-11 illustrates the performance of TPV as extrapolated from laboratory data and goals from funded programs.

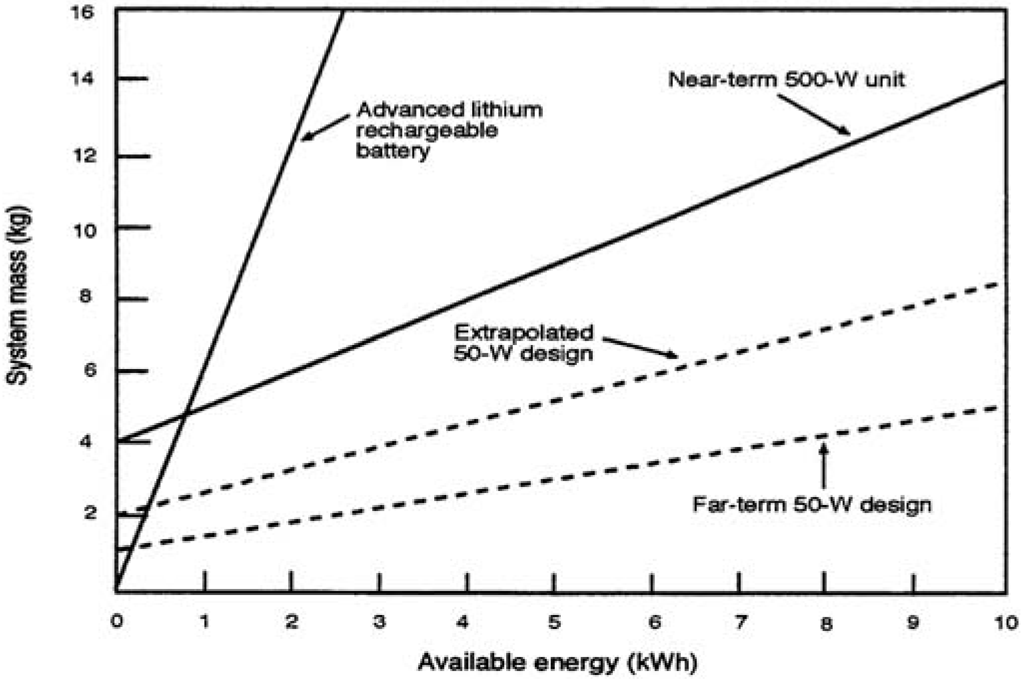


FIGURE C-11 Estimated thermophotovoltaic (TPV) system mass as a function of mission energy for point designs currently funded by DARPA.

Key Research Issues

The potential for TPV power systems has already been demonstrated. The most promising approach for the Army at present is to build prototype systems for evaluation with the research process keyed to correcting system flaws and inadequacies. Several topics must be thoroughly investigated before optimized energy systems can be developed. The most important are:

- liquid fuel combustion in small systems
- bandgap tailoring in photovoltaic materials and devices
- design of cavity structures, including emitter, filter, cell array, and coolant/recuperator schemes
- high temperature recuperators

ELECTROCHEMICAL CAPACITORS

Traditional capacitors are, in general, highly power dense but are incapable of high energy densities. Unlike capacitors, batteries have high specific energies but are incapable of extremely high specific powers. In many situations, the power source must have the best attributes of both, that is, high specific energy and high specific power. In recent years, a class of devices called "electrochemical capacitors" has emerged that have some of the attributes of both batteries and capacitors (Florida Educational Seminars, 1996).

In terms of both specific power and specific energy, electrochemical capacitors are intermediate between classical batteries and capacitors. They have specific energies on the order of 10 to 20 percent of batteries and specific powers at least an order of magnitude better than a conventional batteries. Compared with conventional capacitors, they have specific power an order of magnitude less but specific energy an order of magnitude larger. The Army needs a device with the energy storage capability of a good battery and the power capability of a good capacitor. Electrochemical capacitors are a step in the right direction, and this technology is beginning to emerge in the marketplace. The new capacitors should have an enormous number of applications, including meeting the power needs of the dismounted soldier.

In 1887, Helmholtz discovered that the interface between a conducting material and an electrolyte was capable of storing an electrical charge. The restrictions on the potential storage are associated with the dissociation potential of the electrolyte. If aqueous electrolytes are used, the dissociation potential is the potential necessary to dissociate water through the process of electrolysis, i.e., on the order of 1.20 V. The interface thickness is on the order of 10^{-9} meters for highly conducting electrolytes.

Activated carbon has a surface area greater than 1,000 m^2/g. A capacitor that uses 1 g of material should have a capacitance greater than 1 F and should operate at a voltage on the order of 1 V. Note that the electric field in the interface is on the order of 1 V divided by 10^{-9} m. This corresponds to an electric field of 1,000 MV per meter, an enormous electric field. It is possible to engineer such devices. In 1969, Standard Oil of Ohio (SOHIO) successfully engineered and patented a practical device with these characteristics. SOHIO did not develop the technology but did license it to a Japanese firm. Since that time, firms such as NEC, Isuzu, Panasonic, Matsushita, Murata, and Elna, have continued to develop electrochemical capacitor technology with both organic and inorganic (sulfuric acid) electrolytes.

In the 1970s, B.E. Conway, at the University of Ottawa, discovered that an extremely fast oxidation-reduction (redox) reaction was possible at the surface of some low resistivity oxides. This discovery led to the development of an electrochemical capacitor based on the intercalation of hydrogen ions (protons) into a surface to cause charge separation. This concept has been developed by several firms, such as Continental Group (now disbanded), Pinnacle Research, and Giner, Inc. Obviously, for this technique to be successful, there must be a ready source of hydrogen ions in the electrolyte solution. For best performance, acid or hydroxide electrolyte solutions are used, the most common being sulfuric acid. However, other electrolytes, including some solids, will also work.

Although many oxides will perform satisfactorily, the most common oxide is ruthenium. Unfortunately, in its present format, ruthenium presents considerable problems in scaling-up from laboratory prototypes because the oxide is deposited in a thin-film on a metallic electrode. The thickness of the film is critical, and in addition to the manufacturing technology for producing the thin-film, poor packing fraction results when the film thickness approaches the electrode thickness. Recently, the Army Research Laboratory has developed, a version of the ruthenium technology that promises the manufacturing ease of carbon powder technology while doubling the specific energy associated with ruthenium oxide-based electrochemical capacitors. The specific energy is greater than carbon technology by a factor of three or four.

Because the resistance of any finished device must be minimized, the most desirable materials have low resistivity and maximum surface area. For most practical uses, both energy and power density should be maximized. Although the charge storage mechanisms for different classes of electrochemical capacitors vary, they all need electrolytes that can effectively cover and wet the large surface areas characteristic of electrochemical capacitors. The electrolyte acts as a distributed connection between active storage areas within the capacitor. All practical versions of electrochemical capacitors are composed of two capacitors in series, with the electrolyte forming the interconnecting current path. The electrode can be a porous solid, in which case there is no need for a true separator; it can be a porous compact made up of extremely fine particles, with or without binders; or it can be a surface film. To produce a distributed contact, the two halves of the capacitor must be physically separated by a material that allows conduction by ions but not by electrons. This material is usually a plastic, such as Celgard™, which can have a pore volume of 50 percent or greater. The primary conduction mechanism within the material comprising the energy storage medium is electronic and, in the absence of a separator, would create a short circuit between the halves of the capacitor if they touched.

Particle Bed Chemical Double Layer Capacitor

Helmholtz and others developed the idea that the interface between an ionic conducting electrolyte and an electronic conducting material, such as a metal, could store an electrical charge. Figure C-12 is an illustration of a "particle bed" chemical double layer (CDL) capacitor that is a practical embodiment of this concept (Rose et al., 1994).

At the positive current collector, carbon particles are in physical contact with each other and come into physical contact with the collector to form one continuous physical contact for the capacitor. The electrolyte wets the large surface area carbons, as well as the surface of the collector, forming a distributed contact that acts as a second physical contact for one of the two capacitors in series within an individual cell. The membrane conducts ironically, but not electronically, and physically separates the two sides of the cell. The electrolyte wets the large surface area carbon in the second half, acting again as a distributed contact. Contact between individual carbon particles and the negative current collector form the remainder of the cell. In other words, the cell consists of two capacitors (mirror image around the membrane) in series.

Organic electrolyte CDL capacitors are similar to capacitors with aqueous electrolytes. Because organic electrolyte CDLs can operate at higher voltage, their specific energy should be greater by the square of the ratio of the operating voltage in the organic electrolyte. In practice, however, the specific energy is less because organic electrolytes cannot wet and form double layers in small pores the

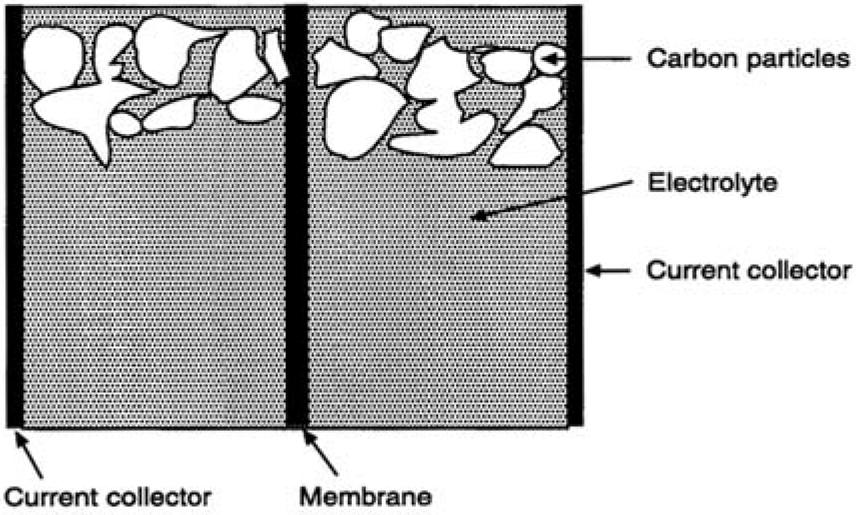


FIGURE C-12 Schematic representation of a particle bed CDL.

way aqueous electrolytes can. Aluminum foils are usually used as current collectors. Because an oxide coating forms on the aluminum, it is particularly stable in organic electrolytes and can be safely operated at voltages as high as 3 V.

In the manufacturing process, the carbon powder is mixed with a suitable binder, such as Teflon™, and processed into a tape. The tape is pressed to a current collector in the form of an aluminum foil or screen, a separator is added, and the ensemble is rolled on a suitable mandrel. The unit is then impregnated with electrolyte and packaged. Because of the high resistivity of organic electrolytes, the planar area of the tape must be high to achieve a low equivalent series resistance (ESR).

This process is suitable for a single cell, but it does not lend itself readily to bipolar stacking, and the units on the market are single-cell, cylindrical packages. This places a burden on high voltage, high energy units because individual cylinders must be packaged and a penalty paid for the packing fraction in addition to the penalty for packaging of the individual cell.

Pseudocapacitors

Pseudocapacitors store energy electrochemically, rather than electrostatically, much like a very fast battery. The only criterion that must be met is that the reaction at the electrode surface be reversible and, of course, rapid:

$$Ox + e\text{`} \quad Red$$

The device must have a species that can be oxidized and reduced reversibly. It is easy to show that:

$$C / Q = d \{ O_x / Q \} / dV$$

where O_x is the fractional charge associated with the oxidation, and Q is the total charge. The capacitance, C, in the above expression is not a true electrostatic capacitance but is the result of the reversible reaction. Putting optimal values in the equation yields a limiting capacitance from this mechanism on the order of 4000 F/ cm ^{3}, which is about an order of magnitude more than the CDL technologies. It is worth noting that real devices do not attain this value, however, and the equation (in effect) is $Q = CV$. That is to say, the adsorption of a charge-bearing species on a surface is a function of the driving point potential, which defines the uniqueness of pseudocapacitors and differentiates them from batteries. Pseudocapacitors have additional internal resistance because the process by which the charge is stored is faradaic (like a battery) and depends on the potential driving the process.

Numerous oxides have been investigated for pseudocapacitance. The most prominent are oxides of ruthenium, iridium, vanadium, nickel, tungsten, cobalt, molybdenum, and some plastics. The mechanism in aqueous electrolytes is the same with respect to storage. In the interest of space, only devices based on ruthenium oxides are discussed in any detail here, although devices based on other oxides are included in the tabular data.

Ruthenium oxide has been found to be an excellent material for pseudocapacitors. The oxide can be anodically formed on ruthenium metal or can be prepared by chemical means using ruthenium chloride as the precursor. Successive redox processes take place reversibly over the range 0.00 to 1.40 V in aqueous sulfuric acid solutions. The states involved over this range are Ru(II), Ru(III), and Ru(IV). Above this potential, hydrogen and oxygen are evolved from the water. The reversibility of the reaction has been established up to approximately 100,000 cycles. The reaction is:

$$RuO_2 + dH^+ + de^- = RuO_{2\text{-d}}\,(OH)_\text{d}\ \ 0 \le d \le 2$$

The highest specific capacitance reported in the literature is on the order of 380 F/g. This material had a specific area on the order of 120 m^2/g. The maximum number of electrons that can be transferred is two for the above reaction. If every ruthenium atom were involved in the transfer process, the specific capacitance would be on the order of 1,000 F/g for a voltage of 1.4 V. The 380 F/g cited above indicates that only about 40 percent of the ruthenium atoms are exposed to the electrolyte solution.

Researchers at the Army Research Laboratory recently discovered that a hydrated amorphous form of ruthenium oxide performed much better than the crystalline version (Zheng and Jow, 1996). The hydrated material is formed by a sol-gel process with precursors of $RuCl_3 \cdot xH_2O$ in a NaOH aqueous solution. At the appropriate pH, $RuO_2 \cdot xH_2O$ precipates in extremely small particulate form. The resistivity of a pressed pellet of the material is on the order of 10^{-3} ohm-cm, a value that is excellent for use in capacitors. The resistivity is determined by the contact area between individual particles in the compact.

After suitable heat treatment, the measured capacitance was 768 F/g, representing more than two-thirds of the theoretical value. The specific capacitance, and hence the specific energy, is a factor of two better than for crystalline ruthenium oxide. This translates into half the cost per joule stored, all other factors being equal. A finished device, a mixture of the particulate and carbon powder, was made using the same technique described above for carbon powder bed capacitors. The current collectors were made from graphitized rubber. Several capacitors were constructed and characterized, and the highest specific energy reported was 8.6 Wh/kg, a phenomenally high value for a small device. The significance of this work is:

- The specific energy is double the density of crystalline ruthenium oxide and three to four times that of carbon technologies.
- The fabrication technique is the same as the well established carbon powder technique.

- The internal resistance is somewhat less than for carbon powder technology but comparable to carbon composite technology.
- Packing fraction is excellent compared with crystalline ruthenium.

The equivalent series resistance (ESR) is typical of aqueous systems and has the disadvantage of all devices that use powder. The ESR depends on the interparticle contact area. High pressures must be applied to the finished compact to achieve the minimum value. This problem is not serious in small devices because crimp sealing of a metal can under pressure is sufficient to produce a minimum ESR.

Equivalent Parallel Resistance

In the charged state, electrochemical capacitors, like batteries, are in a state of high energy relative to the state of minimal energy associated with discharge. As a result, there is a tendency for nonequilibrious states to lower their energy if there is a suitable mechanism for the process to proceed. An ideal capacitor based on polarization would retain a charge indefinitely, but all practical devices tend to self-discharge through a variety of mechanisms. This self-discharge time can be from months (NiCd) to years for some of the solid alkaline batteries available on the consumer market.

The self-discharge time for capacitors will be critical, especially for some of the applications contemplated by the Army. If the power train is a battery-capacitor hybrid, as is envisioned for digital cellular telephones, the self-discharge characteristics of the capacitor must be added to those of the battery. If the self-discharge characteristics of the capacitor are poor, it will require a continual drain on the battery to maintain full charge, which will limit battery life, require more frequent recharging, and reduce the attractiveness of a battery-capacitor hybrid. An isolating switch can be placed between the battery and the capacitor to limit this loss. The battery will still have to recharge the capacitor for each use, but the losses may be less severe than for a capacitor continuously connected to the battery.

Some problems can arise with electrochemical capacitors. If the capacitor is overcharged, the potential will simply drop until it is lower than the dissociation potential. The effect is to reduce the total energy stored. If the capacitance per cell is nonuniform in bipolar stacks, this could result in a substantial reduction of stored energy. The second potential problem is redox reactions caused by impurities in the electrode materials or in the electrolyte. The theoretical treatments for this are complex (Florida Educational Seminars, 1996). From a practical perspective, it is necessary to minimize both the amount and types of impurities that could cause redox reactions. For carbon technology, there are numerous examples of 1 V single-cell devices built with an equivalent parallel resistance (EPR) of several thousand ohms. Table C-22 illustrates the state of the art in electrochemical capacitor technology based on data from technical and manufacturers' literature.

Key Research Issues

Although commercial electrochemical capacitors are available commercially, none has the internal parameters that would allow them to be used in the communications systems envisioned in this report. With further development, this technology could have a favorable impact on the power problem. Pulsed digital communications can reduce the demand for energy while increasing the life of a primary battery or the time between recharges for a secondary battery. Some laboratory prototypes can satisfy many criteria for battlefield use, but they are handmade, and the technology to mass produce devices with acceptable, reproducible results has not been established. The key areas for research are:

- physical phenomena that limit specific energy, specific power, internal series resistance, internal parallel resistance, degradation mechanisms, temperature dependent phenomena, and useful life of electrochemical capacitors
- development of a series of laboratory prototypes for evaluation in hybrid power systems
- development of high voltage electrolytes
- development of low cost materials for use in both the chemical double layer and pseudocapacitors

HYBRID SYSTEMS

Hybrid systems offer an alternative approach to providing portable power and energy. Hybrid systems combine the advantages of a very high specific energy source capable of maintaining the base load with a very high specific power source capable of providing pulse power. This configuration will greatly enhance the power and energy capabilities in small, portable packages. Hybrid systems can also be used as battery chargers and field generators.

Digitization will alter the demand cycle for military communications. Digital transmission is most effective if the transmission is pulsed, which requires high peak power. An analysis of the power requirements for the dismounted soldier indicates that the demand for power will be cyclic, with peaks several times the average. Furthermore, for long periods of time, the demand for power will be almost zero.

TABLE C-22 Summary of Electrochemical Capacitor Technology

Construction			Performance								Status	
Name	Electrode Configuration	Electrolyte	Energy Density (kJ/kg)	Energy Density (kJ/l)	Resistance (ohms/cm^2)	Maximum Power (W/kg)	Cost	Voltage	Typical Capacitanc e (F)	Largest Unit(J)	Basis for Projection	Readiness Level
NEC Supercap	bipolar carbon/carbon composite	sulfuric acid	4.7	6.8	0.16	4	low	15	470	55k	manufacturer specification	commercially available
NEC FY	bipolar carbon	sulfuric acid	1.2	1.98	45	—	low	5	2.2	—	manufacturer specification	commercially available
NEC FE	bipolar carbon	sulfuric acid	0.036	0.65	1.9	—	low	5	1.5	—	manufacturer specification	commercially available
Panasonic	spiral wound, single-cell carbon	organic	7.9	10.4	7	2.7	low	3	470 1,500	6.7k	commercial device	commercially available
Evans	prismatic carbon	sulfuric acid	0.72	1.8	1	—	low	11	—	40k	manufacturer specification	commercially available
Seiko Instruments	polyacene polymer, button cell	organic	6.84	17.6	12	—	—	5	2.5	—	manufacturer specification	commercially available
Pinnacle Research Institute	bipolar pseudocap using mixed oxides (Ru, Ta)	sulfuric acid	18	50.4	$<10^2$	2	high	100	0.01	15k	manufacturer test data	custom order
			46.8	144	$<10^2$		med				theoretical lab projections	
Maxwell/ Auburn	bipolar carbon/ metal composite	KOH organic	4.32 22	7.2 32.4	0.1–0.2 1.5	1.7 3	med med	28 3	12 2,700	6k 12.5k	engineering prototypes	custom order
SAFT	bipolar carbon	organic	10.4	15.8	15	1.2	low	3	175	—	engineering prototype	custom order
ARL	bipolar hydrous RuO_2	sulfuric acid	96 (active material only)	18.7 (active material only)	—	10	high	5	2.72	34	lab cell	—
Livermore National Laboratory	bipolar aerogel carbon particulate	KOH	3.6	5.4	—	—	med	1	35	—	lab cells	—
Sandia National Laboratory	bipolar synthetic, activated carbon	aqueous	5.0	6.1	0.35	1	med	1	3.5	—	lab cells	—
Los Alamos National Laboratory	bipolar conducting polymer on carbon	solid organic	36–72	—	—	—	low	—	—	—	theoretical lab projections	—
Technautics Hypercap	bipolar pseudocap, Ag-anode, C-cathode	Solid $RbAg_4I_5$	1.98	12.6	>1	—	—	0.6	—	—	manufacturer test data	custom order

TABLE C-23 Most Promising Component Technologies for Hybrid Systems

Prime Source	Intermediate Storage Unit
Fueled system	High power density rechargeable battery
Battery	Electrochemical capacitor
Solar photovoltaic	Regenerative fuel cell
Nuclear	Flywheel
Metal-air battery	Superconducting inductor

The demand for electrical power in any system is rarely constant. Typically, the demand is cyclic, with the peak demand far exceeding the average power requirements. Because power sources rarely have both high specific energy and high specific power simultaneously, designers have typically designed power systems to meet the maximum demand to ensure adequate energy for the worst case. Thus, systems may be heavier than necessary, or planners may be forced to plan shorter missions or to resupply the primary energy sources. If the differences between the peak and average demands are large, it is advantageous to combine a high specific energy, low-specific-power source with a low-specific-energy, high specific power intermediate store to provide load leveling, which would meet the demand with substantial mass savings or with longer operational times for the same mass.

Many combinations of energy sources and intermediate storage are in use today, such as portable x-ray machines, photoflash units, electric cars, and portable cardiac defibrillators. Usually these are battery-capacitor systems. However, the principle could be applied equally well to a number of prime source-intermediate storage technologies. The most promising component technologies for the dismounted soldier, are listed in Table C-23.

Any combination of a primary power source and intermediate storage unit is capable of producing a power train suited to pulsed operation. A limited number of combinations are described here. The Army is already investing in solar photovoltaic-battery systems, which have been proven in combat.

Fueled System and Battery Hybrid

All fueled systems will probably be hybrids of one kind or another. Any fueled system operated in the battlefield environment will be subject to conditions under which it will be difficult or impossible to operate. Examples are submersion, extreme dust, and closed or confined spaces where exhaust fumes would be harmful to humans. Even in less extreme situations, a battery may still have to provide initial start-up for the fueled system. Depending on the climate and type of system, the battery may have to provide power for preheating the fuel or system, for initial pump power, or for control power.

TABLE C-24 High Specific Power Batteries for Hybrid Systems

Chemistry	Current Status		Future			
Specific Power (W/kg)	Specific Energy (Wh/kg)	Specific Power (W/kg)	Specific Energy (Wh/kg)	Present Cycle Life (Cycles)	State of Development	
Nickel						
Aqueous	100–200	40–52	150–250	52–70	500–1,000	available
Aqueous (future)	200–500	25–36	250–1,000	30–40	400–800	possible
Bipolar	—	—	200–400	60–80	—	under development
Pb-acid						
Bipolar	200	25–45	—	—	300	available
Bipolar (future)	—	—	300	45–60	300	possible
Thin foil	1,000	5	—	—	300	under development

Data described in the section on fueled systems indicate that they are five to ten times more energy dense than batteries for the same mission profile. Therefore, the fueled system, not the battery, provides practically all of the overall mission energy requirement.

For the fueled system-battery combination, there are at least three battery chemistries that warrant further consideration: nickel-cadmium; lithium; and lead-acid. Tables C-24, C-25, and C-26 show the specific energy, specific power, and

TABLE C-25 Commercial and Developmental High Specific Energy Batteries as Energy Sources in Hybrid Systems

Chemistry	Current Status		Future				
Specific Power (W/kg)	Specific Energy (Wh/kg)	Specific Power (W/kg)	Specific Energy (Wh/kg)	Present Cycle Life (Cycles)	Future Cycle Life (Cycles)	State of Development	
Li-ion/CoO$_2$	100	100	150	150	1,000	2,000	commercially available
Li-ion/Mn$_{2O}$4	70–100	70–100	150	150	300	600+	available soon
Li(c)/polymer/Mn$_{2O}$4	150	150 (est)	200+	200	300	600+	prototype soon
Li(c)/polymer/(CS)$_x$	200[a]	200[a]	400	300	300	600+	prototype soon
Li(c)/polymer/S	200[b]	400[b]	400	600	research	research	research phase

[a] Prototype

[b] Laboratory cells

state of development of battery technologies that could be intermediate stores for a fueled-system battery hybrid (Arthur D. Little, 1996). As shown in the tables, a system consisting of an AMTEC and a 0.5 kg lithium-polymer battery would provide 5.3 kWh of energy, with peaks of 100 W, for a total mass of 5 kg. The battery pack could provide 100 Wh of energy without recharging. In some scenarios, this might correspond to an hour or more of operating capability. A lithium-polymer battery pack that could provide the total energy would have a mass of 26 kg. It is impossible to estimate the weight of the associated electronics and packaging that would be necessary to use this technology in a practical scenario. There is, however, almost a factor of five difference in mass (5 kg to 26 kg) for the same available energy.

TABLE C-26 Potential Fueled Systems for Hybrid Power Systems

System	Specific Power (W/kg)[a]	Specific Energy (Wh/kg)	Status
PEM fuel cell	28	571	prototype
Thermophotovoltaic	25	520	research phase
Alkali-metal thermal-to-electrical converter (AMTEC)	16	1,040	research phase

[a] Calculated for 2 kg of fuel.

An AMTEC-NiCd system designed to perform the same functions would have a similar mass. The weight of a NiCd system for the total energy requirement alone would be on the order of 170 kg. The NiCd battery could meet the total energy demand for about 20 minutes, but the NiCd battery would have to be recharged more often than the lithium—polymer battery. In any case, the total energy available would be dominated by the energy in the fuel. It is assumed that the AMTEC is 20 percent efficient in converting the heat of combustion of JP-8 to usable electricity. For this system, the pulse time would be on the order of hours depending on the scenario. In general, a status monitor for the battery would determine its state-of-charge and command the fueled system to maintain an acceptable level automatically. The individual soldier would have override capability. In most scenarios, the fueled system could maintain an intermediate store at 90 percent or more most of the time.

Battery and Electrochemical Capacitor

A battery-capacitor combination for an energy storage system would exploit the high specific power of a capacitor and the high specific energy of a battery. For this system, the time scale of the peak power delivery intervals would be shifted from the tens of minutes or hours required for the fueled-battery system to minutes or less for the battery-capacitor system. This combination offers a better system for brief pulses of high power, the kind anticipated for portable digital telephones. Meeting this requirement with a battery alone would require a battery that could provide high power pulses at 8 to 10 times normal capacity and would still have maximum life and adequate operational time between charges. Using a capacitor to meet the peak power requirement would provide better operating performance, longer battery life, and better low temperature operation while lowering life cycle costs and a smaller, lighter weight package. Figure C-13 shows a generic power-time profile for a pulsed digital communications system.

In a recent paper, J.R. Miller (1996) developed a simple simulation of a 1 Ah lithium battery in parallel with an experimental electrochemical capacitor. The battery had an open circuit voltage of 4.1 V and an internal resistance of 0.1 ohms. The parameters assumed for the electrochemical capacitor were a capacitance of 1.28 F and an internal resistance of 0.069 ohms. For a repetitive pulse train of 8.3 ms at 10 A spaced by 90 ms, the battery alone was able to provide 12 minutes of operation. The battery-capacitor combination was able to power the system for 61 minutes, an improvement of roughly a factor of five. Simple circuit models were developed that can be used to predict the performance

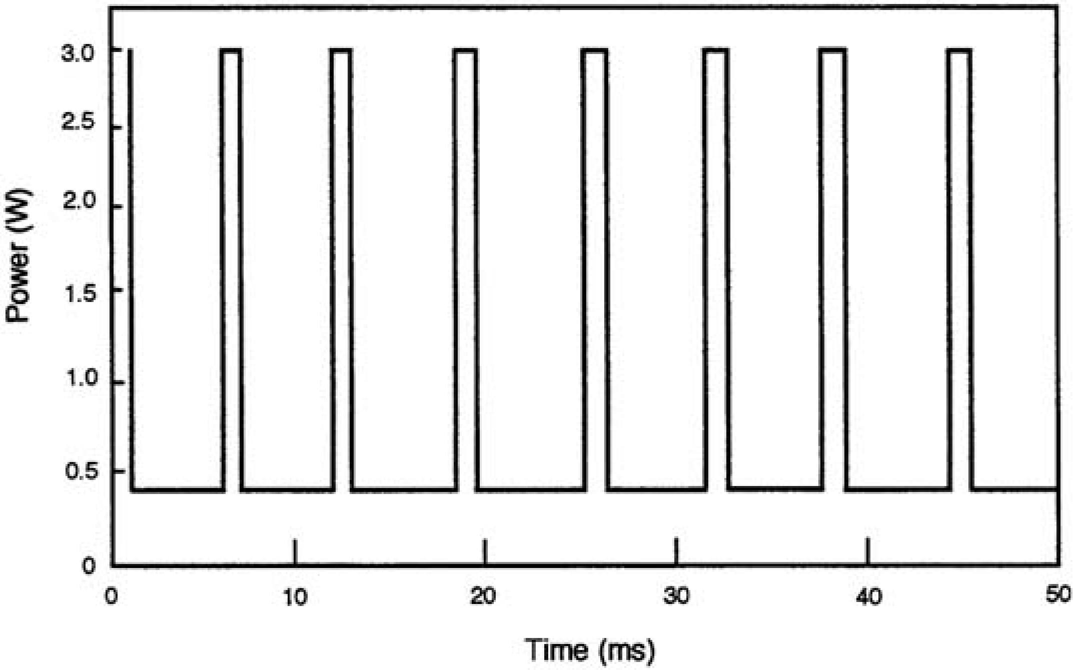


FIGURE C-13 Typical power-time profile for pulsed digital communications devices.

of battery-capacitor combinations accurately. In a similar experimental study, Merryman and Hall (1996) showed that the power train mass for an electrically actuated thrust vector control system for the space shuttle could be reduced by 59 percent when a battery-capacitor combination was used.

TABLE C-27 Energy Storage Media That Could Be Used in Hybrid Systems

Storage Media	State of Art	Energy Density (Wh/kg)	Practical Limit to Specific Power (Wh/kg)	Key Issues	Scaling Laws	Impact	Storage Time
Batteries	highly developed	180–360	~400	electrodes; electrolytes;seals; safety; corrosion	known	major/ enabling	years
Capacitor Film foil Paper foil	highly developed	0.25–1.00	~8.00	molecular engineering of film; manufacturing technology; thermal stability; electrical breakdown	known	enabling for some systems concepts	minutes
Ceramic	highly developed	~0.30	> 3.00	large area samples; electrical breakdown; manufacturing technology	known	enabling for some systems concepts	moderate
Electrolytic	highly developed	< 0.5	> 0.75	large surface area material; suitable oxides; electrolytes	known	minimal	minutes
Chemical double layer	developing	~7.00	> 12.00	large surface area materials; electrolytes; equivalent series resistance/equivalent parallel resistance; seals	known	major	minutes
Magnetic	advanced	> 15.00	strength of materials limited	advanced composites; low resistivity materials	known	minimal	milliseconds
Inertial	highly developed for some applications	100.00	> 300.00	high strength materials; gyroscopic effects; safety	known	minimal	hours/days
Thermal	evolving	sensible heat depends on ΔT	absolute temperature dominated > 5000	materials compatibility; high strength materials; high specific heat	known	uncertain	days/weeks

Table C-27 is a compilation of the characteristics of energy storage media that could possibly be used in hybrid systems. (For completeness, the table includes some media not covered in the text.)

Key Research Issues

Pulsed power techniques have been used extensively in the high-power regimes. Numerous laboratory demonstrations of hybrid systems, typical of systems appropriate for the dismounted soldier, have been performed. To date, there have been no field tests to determine the utility of using hybrid systems for human-portable power. To optimize the design, information on the power demand time history for a variety of mission profiles will be necessary. Given this data, a hybrid system can be designed for the worst case scenario that maximizes the available energy. The key issues are developmental and consist of:

- development of computer models for predicting performance as a function of mission profile
- development of laboratory prototypes
- obtaining reliable field data for the development of energy utilization profiles of the various soldier subsystems

SUMMARY

Table C-28 summarizes the energy and power systems discussed in this appendix. The development of hybrid systems with a fueled primary store would be revolutionary. However, each of the technologies described in Table C-28 has drawbacks. Primary batteries cannot provide the requisite energy for the projected energy budgets of dismounted soldier systems without becoming unstable and creating a significant safety hazard. Primary batteries also pose a significant environmental hazard that will probably increase as new chemistries become available. The primary hazards of batteries are explosive rupture, toxic and corrosive electrolytes, and environmental pollution if they are not recovered. Inevitably, trade-offs among safety, energy, and power considerations will have to be carefully assessed for any system or mission. A secondary battery with the specific energy and specific power of primary batteries would be highly desirable. If this technology were available, the environmental restrictions would be lessened because less frequent recycling would be required. Even a high specific energy rechargeable battery with limited life (say, 50 charge/discharge cycles) would greatly lessen the current problems of supply and disposal.

Any system energetic enough to be considered a major advance for the Army will undoubtedly also be dangerous. Batteries are both energy storage systems and converters in the same unit, and battery safety is closely related to the oxidants and reductants. Consequently, if batteries are designed toward the margin, they have a tendency to explode.

TABLE C-28 Technology Summary of Energy Systems

Power System	State of the Art	Potential for Improvement	Key Issues	Scaling Laws	Impact on Dismount Soldier	Hostile Signature	Suppression Potential	Fuel Required	Autonomy Time
Primary battery	Mature	Moderate	Energy density Safety Power density Environmental impact	Known	Longer mission Less weight Disposability	Minimal	Excellent	None	Hours/days
Secondary battery	Mature	Moderate	Energy density Cycle life Power density	Known	New capability Cost savings Less weight	Minimal	Excellent	None	Hours
Thermophoto-voltaics	Emerging	Excellent	Requires cooling Efficiency Lifetime Ruggedization	Uncertain	New capability Cost savings Longer mission	Thermal	Moderate	Multifuel	Days/weeks
Fuel cells (hydrogen)	Exploratory development	Excellent	Fuel Water management Safety	Known	New capability Less weight Cost savings	Thermal	Excellent	Hydrogen	Days/weeks
Fuel cells (methanol)	Emerging	Excellent	Fuel and fuel crossover Catalyst	Uncertain	New capability Cost savings Less weight	Thermal	Excellent	Methanol	Days/weeks
Alkali-metal thermal-to-electrical converters	Emerging	Excellent	Liquid metal Membranes Pumps/wicks Ruggedization	Uncertain	New capability Less weight Cost Savings	Thermal	Moderate	Multifuel	Days/weeks
Nuclear isotope	Limited	Excellent	Safety Environmental impact Cost Public acceptance	Known	New capability Autonomy	Thermal Nuclear	Moderate	Special	Month/years
Internal combustion	Some versions mature	Moderate to excellent	Fuels Vibration Life	Uncertain	Cost savings Less weight	Thermal Acoustic	Moderate	Multifuel (Some special)	Days/weeks
Microturbine	Emerging	Excellent	Safety	Uncertain	New capability	Acoustic	Difficult	Special	Days/weeks
Thermoelectric	Some versions mature	Moderate to excellent	Efficiency Materials Coupling	Known	New capability Less weight	Thermal	Moderate	Multifuel	Days/weeks
Human powered	Nonexistent	Excellent	Conversion mechanisms	Unknown	New capability Cost saving Autonomy	Minimal	Excellent	Food	Weeks

In fueled systems, the energy dense fuel is in a separate enclosure and is slowly exposed to the oxidant so that only the fuel that is in the converter at any given time is subject to inadvertent catastrophic failure. With the exception of hydrogen, all of the other fuels are rather involatile, that is, they can burn rapidly but will probably not explode. Fuels are housed in external tanks, which would be subject to penetration and burning if the penetration were energetic enough to ignite them.

Primary batteries will be used in military systems for the foreseeable future. There will, however, continue to be problems associated with their disposal, inventory, safety, and availability, and wherever possible, they should be replaced. The logical evolution of the Army power system for the dismounted soldier is toward a rechargeable battery with improved specific power and energy that would meet or exceed the power available with current primary batteries coupled with a "personal" charger that contains the primary store of energy for the mission. For many missions, the rechargeable battery alone would have enough energy. In those cases, the battery would be returned to the inventory after being recharged. For longer missions, the primary store would be fueled by a standard battlefield fuel. All of the fueled systems described in this appendix offer the possibility of long life with thousands of refuelings, and all of them are at a stage at which advanced development is possible. Coupled with a suitable rechargeable battery with similar cycle capability, these systems would dramatically reduce the inventory necessary to maintain combat readiness. The primary logistic consideration would be—as it is now—fuel supplies. Because batteries could be recharged many times, recycling after each mission would not be necessary, which would greatly reduce their adverse environmental impact.

High specific energy rechargeable batteries are becoming increasingly important in the commercial sector, which could provide the Army with a secure, high volume, guaranteed source of batteries. "Smart" chargers and power management circuitry will also be forthcoming from the commercial sector.

REFERENCES

Army Materiel Command. 1992. Soldier as a System Symposium/Exposition. Proceedings of a symposium sponsored by the Army Material Command, June 30–July 1, 1992, Arlington, Virginia.

Arthur D. Little, Inc. 1996. Proceedings of the Fourth International Conference on Power Requirements for Mobile Computing and Wireless Communications, Santa Clara, California, October 1996. Available from Giga Information Group, One Long water Circle, Norwell, Mass. 02061.

Bass, J.C., N.B. Elsner, and F.A. Levath. 1994. The preliminary design of a 500 W thermoelectric generator. Pp. 586–591 in Proceedings of the 29th Intersociety Energy Conversion and Engineering Conference. AIAA-94-4197-CP. Reston, Virginia.: American Institute of Aeronautics and Astronautics.

Benner, J.P., T.J. Coutts, and D.S. Ginley, eds. 1995. Proceedings of the Second NREL Conferences on the Thermophotovoltaic Generation of Electricity. AIP Conference Proceedings 358. Woodbury, N.Y.: AIP Press.

Florida Educational Seminar. 1996. Proceedings of the Sixth International Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Boca Raton, Florida. Boca Raton: Paumanok Publications, Inc.

Halpern, G. 1997. Personal communication from Gerald Halpern, NASA Jet Propulsion Laboratory, with M.F. Rose, member of the Committee on Electric Power for the Dismounted Soldier, January.

IEEE (Institute of Electrical and Electronics Engineers). 1996. Proceedings of the 20th–25th Photovoltaics Specialists Conferences. Piscataway, N.J.: Institute of Electrical and Electronics Engineers.

Ivanenok, J.F., R.K. Sievers, and T. Hunt. 1993. High Power Density AMTEC . Pp. 861–865 in Proceedings of the 28th Intersociety of Energy Conversion and Engineering Conference, Atlanta, Georgia. Reston, Virginia: American Institute of Aeronautics and Astronautics.

Ivanenok, J.F., and T.H. Hunt. 1994. High voltage terrestrial AMTEC. Pp. 900–909 in Proceedings of the 29th Intersociety Energy Conversion and Engineering Conference, Monterey, Calif.. Paper no. AIAA-94-3903-CP. Reston, Virginia: American Institute of Aeronautics and Astronautics.

Merryman, S.A., and D.K. Hall. 1996. Chemical double layer power source for electromechanical thrust vector control actuator. Journal of Propulsion and Power 12(1): 89–94.

Miller, J.R. 1996. Battery-capacitor power source for digital communication applications: simulations using advanced electrochemical capacitors. Pp. 246–255 in Proceedings of the Symposium on Electrochemical Capacitors. F.M. Delnick and M. Tomkiewicz, eds. Proceedings Volume 95-29. Pennington, N.J.: Electrochemical Society.

Morton, D. 1952. Human Locomotion and Body Form. Baltimore: The Williams and Wilkins Co.

NTSE. 1992. Nuclear Technologies for Space Exploration. (NTSE '92). Proceedings of a conference held in Jackson Hole, Wyoming, August 16–19. 3 vols. Grange Park, Illinois: American Nuclear Society, Idaho Section.

Raskovich, E., ed. 1993. Front End Analysis of Soldier Individual Power Systems. USA-BRDEC-TR//2541. Ft. Belvoir, Va.: Belvoir Research, Development and Engineering Center. May.

Rose, M.F., C. Johnson, E. Owens, and B. Stevens. 1993. Limiting factors for carbon-based chemical double layer capacitors. Journal of Power Sources 47: 303–313.

Rowe, D.M., ed. 1988. Proceedings of the First European Conference on Thermoelectrics. Stevengate, Hertsfordshire, U.K.: Peter Peregrinus, Ltd.

Salkind, A.J. 1996. Estimate by A.J. Salkind, presented to the Battery Division of the Electrochemical Society at its annual meeting, San Antonio, Texas, October 6.

Schuller, M. 1997. Personal communication from Dr. Michael Schuller, U.S. Air Force, Phillips Laboratory, to M.F. Rose, member of the Committee on Electric Power for the Dismounted Soldier.

Space Power Institute. 1990. Mobile Battlefield Power Workshop. M.F. Rose, ed. Results of a workshop held in Durham, North Carolina, October 30–November 1, 1990. 2 vols. Sponsored by the Army Research Office, Contract No. DAAL03-86-D-001. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1992a. RTG Power Applications Workshop. M.F. Rose, ed. Results of a workshop held in Park City, Utah, March 22–25, 1992. Sponsored by the Army Research Office, the U.S. Department of Energy, and the Jet Propulsion Laboratory. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1992b. Prospector III: High Energy Density—High Power Density Power Sources RD Workshop. M.F. Rose, ed. Results of a workshop held in Auburn, Alabama, May 26–28, 1992. Sponsored by the Army Research Office. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1992c. Prospector IV: Small Engines and Their Applicability to the Soldier System Workshop. M.F. Rose, ed. Results of a workshop held in Durham, North Carolina, November 10–12, 1992. Sponsored by the Army Research Office. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1994. Prospector VII: Small Fuel Cells for Portable Power Workshop. C.R. Johnson and M.F. Rose, eds. Results of a workshop held in Durham, North Carolina, October 31–November 1, 1994. Sponsored by the Space Power Institute and the Army Research Office. Auburn, Alabama: Space Power Institute.

Space Power Institute. 1996. Prospector VIII: Thermophotovoltaics—An Update on DoD, Academic, and Commercial Research. C.R. Johnson and M.F. Rose, eds. Results of a workshop sponsored by the Army Research Office, Durham, North Carolina, July 14–17, 1996. Auburn, Alabama: Space Power Institute.

Starner, T. 1996. Human-powered wearable computing. IBM Systems Journal, 35(384): 618–629.

Tan, C., Y. Tzeng, I. Waitz, R. Walker, D.J. Orr, S. Senturia, A. Ayon, J. Mur Miranda, E. Piekos, C. Lin, A. Epstein, M. Spearing, G. Anathasuresh, K. Breuer, K.S. Chen, F. Ehrich, E. Esteve, G. Gauba, S. Jacobson, J. Lang, A. Mehta, S. Nagle, and M. Schmidt. 1997. Micro Gas Turbine Generators. Interim technical progress report for Grant DAAH 04-95-1-0093, Army Research Office, Research Triangle Park, North Carolina.

Zheng, J.P., and T.R. Jow. 1996. High energy and high power density electrochemical capacitors. Journal of Power Sources, 62: 155–159.

Appendix D

Future Directions for Low Power Electronics

For nearly four decades, low power silicon microelectronics have improved exponentially in both performance and productivity. The switching energy, or power-delay product, of a binary transition has been reduced by about five orders of magnitude, and the number of transistors per chip has increased by about eight orders of magnitude. At the same time, the price range of chips has remained almost constant. The National Technology Roadmap for Semiconductors (NTRS) projects a 64-billion-bit dynamic random access memory (DRAM) chip by 2010 (Semiconductor Industry Association, 1994). Perhaps the most compelling questions confronting the surging $150 billion worldwide semiconductor industry are how much further the laws of physics (and economics) will enable this progress to continue and what the critical limits most likely to determine how many billions of transistors we will manufacture in future commercially viable low power silicon chips are. Several focused efforts to address this question have been reported in the last two decades (Keyes, 1975a, 1979; Meindl, 1983, 1995).

The central thesis of this appendix is that early twenty-first century opportunities for low power gigascale integration (GSI) will be governed by an ordered progression or hierarchy of theoretical and practical limits, whose five levels can be classed as fundamental limits; material limits; limits on device; limits on circuit; and limits on systems (Meindl 1983, 1995). The following section reviews recent enhancements of this hierarchy and identifies the critical limits that present the most formidable challenges to continued progress toward low power GSI.

THEORETICAL LIMITS

Energy transfer per binary transition is a very useful metric for comparing the performance of switching operations at all levels of the hierarchy of limits on low power GSI. Using logarithmic coordinates in the power-delay plane, where the ordinate is the average power transfer during a binary transition, P, and the abscissa is the delay time of the transition, t_d, results in a diagonal constant switching energy locus, $E = Pt_d$. Interconnect performance can also be illustrated at all levels of the hierarchy in a logarithmic plot of "reciprocal length squared,"

L^{-2}, versus response time, τ, where L is the distance traversed by an interconnect that joins two nodes on a chip and τ is the response time of the interconnect circuit. Using logarithmic coordinates in the L^{-2} vs. τ plane results in a diagonal constant distributed resistance, r_{rint}, capacitance, c_{cint}, locus $L^{-2}\tau = r_{\mathrm{int}}c_{\mathrm{int}}$, for an interconnect. For continued improvements in low power electronics, both the $E = Pt_{\mathrm{d}}$ and $L^{-2}\tau = r_{\mathrm{int}}c_{\mathrm{int}}$ loci must migrate toward the lower left corners of their displays.

Fundamental Limits

At the first level of the hierarchy are three fundamental limits on low power electronics (Meindl, 1995). Derived from thermodynamics, the first of these is a result of the random thermal motion of carriers in solids. This limit imposes a minimum switching energy, E, on a binary transition of approximately 2 to 4 kT or 0.05 to 0.1 eV at room temperature, where kT is the familiar thermal energy. Quantum mechanics, and more specifically the Heisenberg uncertainty principle, defines the second fundamental limit, which requires a switching energy $E > h/t_{\mathrm{d}}$, where h is Planck's constant and t_{d} is the transition time, for $t_{\mathrm{d}} = 1.0\ ps$, $E > 0.004\ eV$. The propagation velocity of an electromagnetic wave traveling in free space ($c_{\mathrm{o}} = 3 \times 10^{10}$ cm/sec) determines the third fundamental limit.

Within these fundamental limits, the switching energy required to overcome the thermal energy of an electron, as well as the energy uncertainty resulting from its wavelike behavior, are orders of magnitude smaller than projected system limits on switching energy. (A fundamental opportunity for further reducing energy dissipation in binary switching operations, derived from the second law of thermodynamics, is based on conserving or recycling switching energy by maintaining constant entropy in a computing engine. This approach is practical for a limited range of applications). Nevertheless, the propagation velocity of a high-speed pulse traveling on an effectively lossless global interconnect now approaches 50 percent of the velocity of light in free space. Consequently, it appears that the most binding fundamental limit is currently determined by the velocity of light.

Material Limits

There are four material limits at the second level of the hierarchy. Three are imposed by semiconductor materials and the fourth by interconnect materials (Meindl, 1995). A switching energy limit is defined by the amount of energy that must be stored in a cube of semiconductor material to produce a binary transition voltage of 1 V. (The selection of a 1 V transition is justified in the following discussion of circuit limits). This energy—about 10 eV—is approximately 20 percent larger for silicon (Si) than for gallium arsenide (GaAs), an insignificant difference.

A transit time limit is determined by the interval required for an electron to be transported through the cube. For Si, this interval is about 0.33 ps, assuming that the material operates at its breakdown field strength and carrier saturation velocity. This transit time limit is 33 percent larger for Si than for GaAs, again an insignificant difference.

The third key material limit is defined as the intrinsic switching delay per unit of heat removal of a generic device located at the top surface of a chip whose bottom surface is in contact with an ideal heat sink. This heat-conduction-limited delay is about three times as large for GaAs as for Si, because GaAs has three times the thermal resistivity of Si. In this instance, Si offers a significant advantage.

The fourth material limit is the propagation velocity of an electromagnetic wave in a uniform dielectric material whose relative permittivity is greater than unity. For a typical dielectric, such as SiO_2, the value of this limiting velocity is roughly 50 percent of the corresponding fundamental limit for virtually lossless interconnects. (For lossy interconnects, the relaxation time, $\tau = \rho\varepsilon$, where ρ is the conductor resistivity and ε the dielectric permittivity, represents the key material limit.)

The implications of the three semiconductor material limits are that switching energy and transit time constraints imposed by semiconductor materials per se are well below those projected for the system level, and that Si is indeed the semiconductor material of the future for low power GSI. The interconnect materials of the future are unclear but, as at the fundamental level, the time-of-flight of an electromagnetic wave appears to be the most binding material limit for virtually lossless interconnects.

Performance Limits on Devices

Proceeding to the third level of the hierarchy, the key limits on low power electronics are imposed by the switching energy and delay of a metal-oxide-semiconductor field effect transistor (MOSFET) and the response time of an interconnect (Meindl, 1995). Both MOSFET limits are defined largely by its minimum allowable effective channel length, L_{min}, at an assumed drain voltage of 1.0 V. Analytical and numerical calculations as well as recent experimental data show that L_{min} for a bulk MOSFET with a uniform channel doping profile is about 100 nm, assuming a 3.0 nm gate oxide thickness in order to avoid tunneling current, a maximum drain voltage of 1.5 V, and a threshold voltage of 0.35 V. The corresponding switching energy is approximately 10_4 eV. For an abrupt retrograde channel doping profile, L_{min} drops to about 50 nm. For a symmetrical dual-gate silicon-on-insulator (SOI) MOSFET, a device that we do not yet know how to manufacture, the projected L_{min} is approximately 25 nm. Postulating a bulk MOSFET with a yet-to-be-demonstrated high-permittivity gate dielectric stack, an L_{min} in the range of 25 nm can be projected. Finally, an additional opportunity for achieving a sub-25 nm channel length is based on reducing gate oxide thickness below the 3.0 nm tunneling limit to the 1.5 to 2.0 nm range, which is still sufficiently large that MOSFET gate current would be small compared to the average current drain of a typical logic circuit.

The strong message conveyed by the foregoing discussion of MOSFET scaling limits is that we have more than 20 years of device scaling in the offing—if the historic level of inventiveness is maintained. This 20 year projection assumes that the current rate of scaling minimum feature size will persist at least through the 125 nm generation of technology and thereafter will not fall below one-half its current rate, as noted in the following discussion of practical limits.

Although MOSFET scaling richly benefits both performance and productivity, the impact of scaling interconnect dimensions is markedly different. A critical device level limit is defined by the response time of an interconnect. Using a canonical distributed resistance-capacitance network as a model, response time is given by $\tau = r_{\mathrm{int}} c_{\mathrm{int}} L^2$, as described in the opening paragraph of this discussion of theoretical limits. For example, assuming a 1.0 mm technology, the minimal 10 ps switching delay of a MOSFET is 10 times as large as the response time of a 1.0 mm long interconnect implemented with Al and SiO_2. But, for 0.1 mm technology, the 100 ps response time of a 1.0 mm interconnect is at least ten times larger than the switching delay of a MOSFET. Moreover, for 0.1 mm technology, the switching energy of a 1.0 mm interconnect is greater, by a factor of approximately 1,200, than the switching energy of a minimum size MOSFET. This simplified example clearly suggests that the most binding device performance limits on low power GSI will be imposed by interconnects and not by MOSFETs—unless current circuit and system configurations are significantly altered to avoid the use of long interconnects.

As the number of interconnects multiplies, innovative techniques and technologies will be required to reduce wire capacitance. Integrating memory with logic by use of emerging integrated memory technology will allow interconnect lengths to be kept short by eliminating the need for high-capacitance external memory access. Significant advances have also been made in the area of low-swing drivers and in techniques ranging from adding regulators on-chip to energy recovery approaches.

Limits on Circuits

At the fourth level of the hierarchy, there are four generic circuit limits on low power electronics imposed by the static transfer characteristic of a logic gate, by the power-delay product or switching energy of the gate, by its propagation delay time, and finally by the response time of a global interconnect circuit (Meindl, 1995). To maintain the quintessential capability to restore binary "zero" and "one" levels virtually without error throughout a large digital system, the transfer characteristic of a complementary metal-oxide semiconductor (CMOS) logic gate must have a slope with an absolute magnitude of at least unity at the transition point where input and output signals are equal.

Imposing this quantizing constraint on the transfer characteristic of a CMOS inverter circuit reveals that the minimum allowable supply voltage of CMOS circuits is approximately 2 to 4 kT/q or 50 to 100 mV at room temperature. Then, one may ask, why not immediately reduce supply voltage from the 3.0 V range now commonly used to the 50 to 100 mV range and thereby reduce the energy per switching transition by three orders of magnitude? To do so without sacrificing performance would require scaling down threshold voltage, V_t, roughly in proportion to the reduction in supply voltage, V_{dd}. Because MOSFET subthreshold current increases exponentially as threshold voltage is reduced, the result of such drastic scaling of supply and threshold voltage would be an unacceptably large static current drain in a CMOS logic circuit.

A more interesting question to ask, therefore is, what the optimal value of supply voltage that minimizes the total energy is or what the average power dissipation per clock cycle of a typical gate circuit in a complex logic network is. Note that the total energy consists of the sum of the dynamic (or switching) energy and the static (or standby) energy drain during a clock period whose value is determined by performance requirements. A simplified expression for this optimal supply voltage (Bhavnagarwala et al., 1996) indicates its dependence on: S, MOSFET subthreshold swing ;μ, subthreshold channel carrier mobility; n_{cp}, the number of gates in the critical path of the logic network; a, the network activity factor or probability that a gate will switch during a given clock cycle; b, the fraction of a clock cycle available for logic operations or the clock skew factor; v_{sat}, the channel carrier saturation velocity; L, the effective channel length; and V_{dd}/V_t, the ratio of supply voltage to threshold voltage determined by performance requirements.

Clearly, each MOSFET technology and each logic network configuration defines its own optimal supply voltage for low power operation. Computing values of V_{dd} (opt) for a wide range of device and logic network parameters indicates that V_{dd} (opt) = *1.0 V* is a midrange value that is broadly advantageous. Consequently, a 1.0 V supply voltage is used to compute limits at the material, device, circuit, and system levels of the hierarchy of limits on low power electronics.

For a specified supply voltage, V_{dd}, and total circuit load capacitance, C_c, the switching energy limit $E = (1/2)\ C_c\ (\mathrm{Vdd})^2$ has a value of about $4\mathrm{x}10^4$ eV for 100 nm technology. The corresponding propagation delay limit, t_d, is approximately 0.01 ns (Meindl, 1995). The fourth circuit limit is the response time of a global interconnect circuit consisting of the interconnect itself and a driver stage, whose output resistance is matched to the characteristic impedance, Z_o, of the global interconnect. The response time limit is given approximately by $\tau = 2.3(L/v)$ where L is the length and v is the velocity of wave propagation of the interconnect (Meindl, 1995).

Which of the four key circuit limits appears to be the most formidable barrier to the progress of low power GSI? Assuming lightly loaded gate circuits, more like those found in a ring oscillator than in a fully loaded system environment, a representative circuit level propagation delay limit for 100 nm technology will be taken as 0.01 ns. For a global interconnect length of $L = 3.0$ cm, a representative value of the circuit response time is $\tau = 0.46$ ns, which assumes the use of "fat" conductors (Sai-Halasz, 1995) with a 1.5 × 1.5 µm cross section and neglects skin effect. The fat conductors reduce total interconnect DC resistance to less than 2.3 times the driver transistor output resistance. Once again, it appears that limits associated more closely with interconnects than with MOSFETs impose the dominant circuit level constraints on the performance of low power GSI. This observation tends to hold true for both "RC-limited" minimum-geometry local interconnects as well as for "LC or time-of-flight-limited" fat global interconnects.

Limits on Systems

System limits are by far the most numerous and nebulous limits in the hierarchy. At the same time, they are also the most restrictive, and we are therefore compelled to pay close attention to them. Among the virtually countless system limits are five generic constraints that apparently cannot be avoided. These limits are imposed by the architecture of a chip; by the switching energy of its semiconductor technology; by the energy storage capacity of low power portable systems or the heat removal capacity of the packaging technology of desk-top systems; by operating cycle time; and finally, by the size of the chip containing the low power system (Meindl, 1995). To exploit the advantages of sub-100 nm MOSFETs and preclude the negative effects of relatively long (and therefore slow) local and global interconnects, radically new chip architectures must be engaged. The period of avoiding this problem is over.

Historic shifts in architectural style in order to exploit fully the strengths of available implementation technologies have occurred in the past. Prior to the advent of integrated circuits, discrete transistors were expensive, and passive parts were economical, prompting ancient design styles that minimized the use of transistors. The extremely limited menu of resistors, capacitors, and inductors offered by monolithic semiconductor technology quickly brought forward design styles that virtually excluded all passive components, with the notable exceptions of small capacitors in DRAMs and poor resistors in static random access memory (SRAMs). To reiterate, in order to continue to capture the benefits of MOSFET reductions in scale in low power systems, we simply must have architectural innovations that preclude, or at least drastically reduce, the need for long local and global interconnects. Systolic arrays exemplify such architectures (Kung, 1982).

The system level switching energy limit closely parallels the corresponding circuit level limit, with the distinction that capacitive loading is much greater because of the longer interconnects. The need for early but reliable estimates of capacitive loading of random logic networks is acute, in order to estimate chip size, power dissipation, performance, and cost. Recently, a new derivation of a complete stochastic frequency distribution of chip wiring, including local, semiglobal, and global interconnects, was reported (Davis, et al., 1996). Figure D-1 illustrates a comparison of the predictions of this distribution with actual data. A valuable result of the distribution is an improved capability to project the switching energy limit and power dissipation for a given system on a chip. This projection must be based on critical path models, including both a chain of random logic gates and a global interconnect circuit (Meindl, 1995).

For low power portable systems, the third generic system limit simply requires that the total power dissipation of a chip, P_s, be less than E_b/T_b, where E_b is the allotted battery energy for the chip and T_b is the operating interval between battery rechargings. For desk-top systems, this limit requires that $P_s < QA_s$, where Q is the package cooling coefficient (dimensionally W/cm^2) and A_s is the chip area. To satisfy timing constraints, the fourth generic system limit imposes the requirement that the total cycle time, T_c, must be less than the maximum value of clock skew, T_{cs}, plus the critical logic path delay, T_{cp}, which consists of both a random logic portion and a global interconnect portion. The global interconnect response time depends on the size of the chip and thus engages the final system limit.

A rather complicated looking, but piece wise simple, composite plot illustrating the entire hierarchy of theoretical limits on low power GSI in the power versus delay plane is presented in Figure D-2. The curves are labeled as follows: (1) fundamental limit from thermodynamics, (2) fundamental limit from quantum mechanics, (3) material limit on switching energy, (4) material limit on transit time, (5) material limit on thermal conduction capacity, (6) device limit on switching energy, (7) device limit on transit time, (8) circuit limit on switching energy, (9) circuit limit on propagation delay time, (10) system limit on switching energy, (11) system limit on heat removal, and (12) system limits on cycle time and chip size.

The system limits apply to a one billion gate system organized as a 32 × 32 systolic array of "random-logic-like" macrocells; implemented with 100 nm CMOS technology in a 4.54 × 4.54 cm die; enclosed in a package with a 50 W/cm^2 cooling capacity; and operating at a 1.0 GHz clock frequency. The allowable design space for the target system is the small triangle whose vertices are labeled t_{dmin}, corresponding to the maximum performance system (and therefore minimum propagation delay time) that 100 nm semiconductor technology in a 50 W/cm^2 package can provide; P_{min}, corresponding to the minimum power dissipation (per switching transition) that the system can accommodate for 1.0 GHz operation; and P_{max}, corresponding to the maximum power dissipation (per switching transition) and therefore the largest minimum feature size and presumably the most mature and lowest cost technology that can provide 1.0 GHz performance in a 50 W/cm^2 package.

The system parameters for this example were selected to illustrate the very limited design window that will exist for one billion gate, 100 nm, 1.0 GHz GSI technology. Power dissipation can be reduced drastically simply by derating performance, which in effect moves the right boundary of the design triangle to the right, corresponding to larger propagation delay times (i.e., values of t_{dmin}) at the system level.

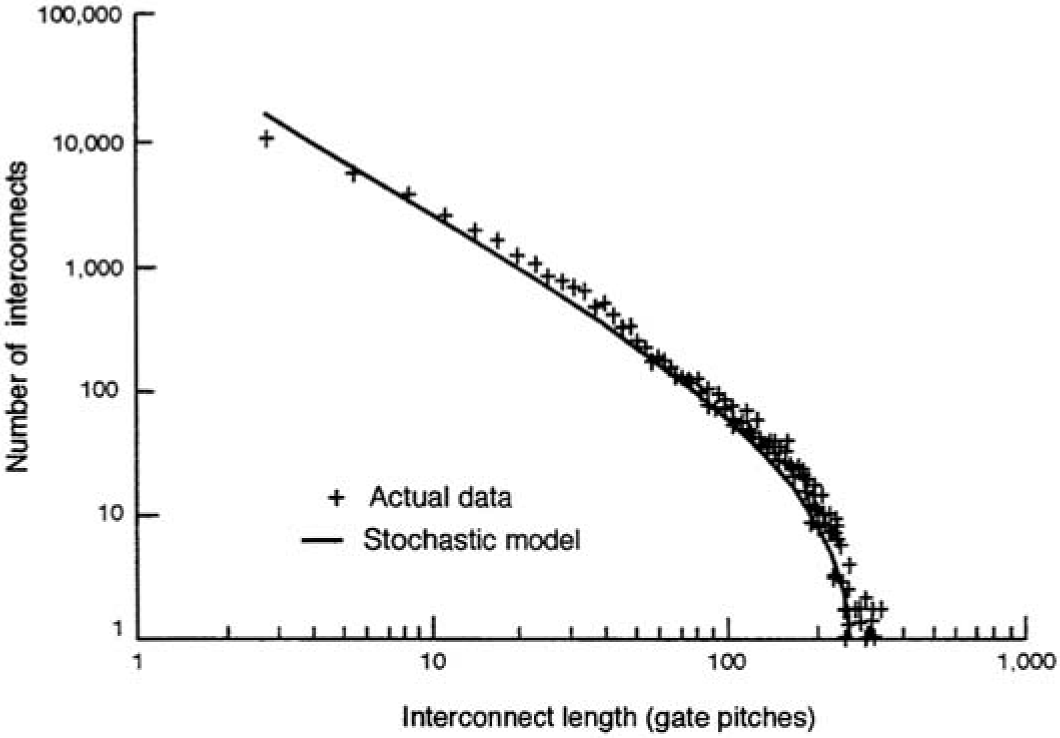


FIGURE D-1 Interconnect length distribution density function: interconnect length distribution density versus interconnect length.

Practical Limits

Practical limits on low power GSI must, of course, be in compliance with the theoretical constraints but must also take into account manufacturing costs and markets, which are governed by the laws of economics. In light of our understanding of the key physical limits on the performance of low power GSI, the paramount question to be addressed is how many transistors we can expect to manufacture in a single Si chip that will prove to be commercially viable at some specified future time. Therefore, our focus is shifting from performance limits to productivity limits. The number of transistors per chip, N_{tr}, can be expressed rather elegantly in terms of three macrovariables that measure our rate of progress toward GSI. This expression is $N_{tr} = F^{-2} x D^2 x (PE)_{tr}$, where F is the minimum feature size, D is the square root of die area and $(PE)_{tr}$ is the packing efficiency of transistors in units of transistors per minimum feature square (Meindl, 1995).

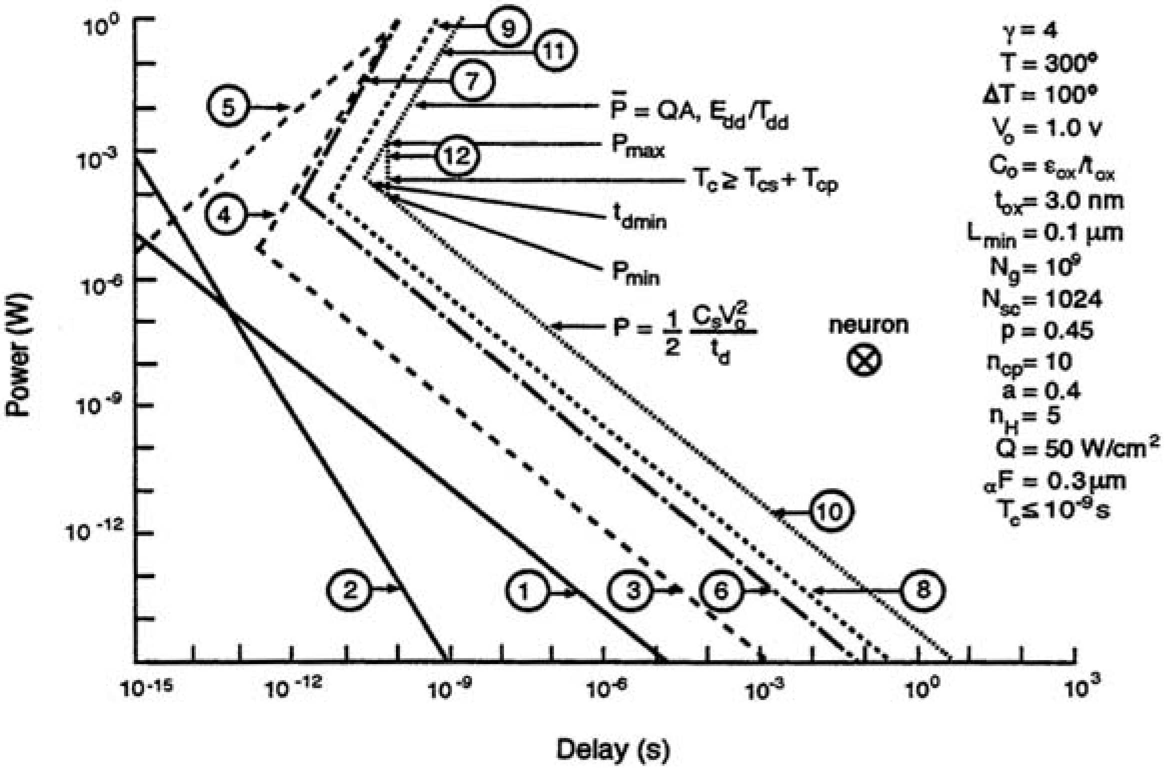


FIGURE D-2 Average power transfer per binary switching transition, *P*, versus transition time, t_d. Source: Chandrakasan and Brodersen. 1995.

Both retrospectively and prospectively, scaling down minimum feature size is the single most potent contributor to improvements in both the performance and productivity of low power microelectronics. Small scale integration in 1960 began with average values of *F* = 25 µm. By 1980, *F* had been reduced to approximately 2.5 mm and, if the historic rate of scaling persists as expected for the remainder of this decade, *F* will reach an average value of 0.25 µm for state of the art commercial chips by the turn of the century. Beyond 2000, minimum feature size is expected to continue to scale down at approximately its historic rate of 50 percent every six years until we arrive at the 0.125 mm generation of chips about a decade from now. At that juncture, a break point in the F versus year, *Y*, curve is expected, owing to a combination of technological and economic factors (which have proven to be highly unpredictable in the past!).

One, and only one, of many possible scenarios that may follow is that optical lithography will finally, as at some point it must, reach its practical limits—at the 0.125 µm generation of chips (or shortly thereafter). When this occurs, possible alternatives include extreme ultraviolet (EUV) or soft x-ray lithography. The relatively short wavelengths of this alternative apparently will require new photon sources, new masking techniques, new resist materials and processes, and new metrologies. The challenges that these prospective advances present appear to be disproportionately more difficult than those that the semiconductor community has met successfully throughout its history.

The same conclusion may well be warranted regarding virtually all of the associated ultra clean sub-0.125 µm fabrication processes, such as ion implantation, rapid thermal processing, and plasma enhanced chemical vapor deposition, which must accompany a new pace-setting suboptical lithography technology in a manufacturing environment (Ohmi, 1994). Consequently, a break point in the *F* versus *Y* curve in the near vicinity of the 0.125 µm generation of chips appears to be a plausible scenario on the basis of the technological challenges to be met. Briefly referring to economic issues, a forceful argument that supports this forecast is that the rapidly escalating costs of the entire suite of sub-0.125 µm manufacturing technologies will require more than a three year period between successive generations of products in order to recover costs and operate profitably.

Assuming this breakpoint scenario, what is likely to follow? In the past, one salient change in the rate of advance of microelectronics technology occurred about 1972, when the rate of increase of die size, *D*, and the rate of increase of transistor packing efficiency, $(PE)_{tr}$, abruptly declined, causing the time interval for doubling the number of transistors per chip to increase from 12 to 18 months (Meindl, 1995). In general, technological historians have often observed that many commercial technologies, such as structural materials, automobiles, aircraft, and lighting, consistently tend to follow a characteristic "S-shape," or sigmoidal, pattern of development when the state of the art is plotted against calendar year (Meindl, 1983). Initially, during a post-discovery or invention phase, the rate of advance is slow, mainly due to resource limitations. This period is followed by an intermediate period of rapid progress due to large investments in competing commercial operations. A concluding phase is marked by only incremental improvements, due to approaching physical limits, causing saturation of a mature technology.

The general occurrence of this pattern prompts speculation that the approximate time interval to reduce *F* by 50 percent will increase from 6 to 12 years following the 0.125 mm generation. At this reduced rate, scaling should be expected to continue through the later years of the second decade of the next century. Then, scaling of bulk MOSFETs is projected to terminate due to a soft collision with their limiting allowable dimensions in the 0.0625 to 0.050 µm range. Beyond that point, however, lie further opportunities for scaling through reduction of gate oxide thickness below the 3.0 nm tunneling limit and through SOI MOSFETs, so that at this point we do not yet see the saturation of a mature MOSFET scaling technology imposed by physical limits.

Projections of trends in minimum feature size depend on understanding theoretical limits, based on relatively well understood principles of physics. Unfortunately, this is not the case for scaling chip dimension, *D*, or transistor packing efficiency, $(PE)_{tr}$. However, two variables that have consistently been rather closely related to chip dimension are minimum feature size and wafer diameter. Throughout the past two decades, both *F* and *D* have maintained constant rates of scaling, and no changes in these rates are projected for about the next decade (Meindl, 1995). Beyond the 0.125 mm generation of chips, the simplifying assumption is made that the time interval of a 50 percent reduction of F is equal to the interval of a 50 percent increase of D. Maximum wafer diameter is projected to reach 300 mm by 2000 and 400 mm by 2010 (Semiconductor Industries Association, 1994). Transistor packing efficiency, $(PE)_{tr}$, has improved at a steady rate for more than two decades, and no change in this value is projected, which implies the rather startling forecast of about one MOSFET per minimum feature square by 2010. This achievement is not imaginable without multiple levels of thin-film transistors, stacked transistors, and side wall transistors, such as we are beginning to see in high density SRAM and DRAM chips. Moreover, today common use of multiple levels of interconnections prompts the projection of multiple levels of transistors.

Following individual projections of the three macrovariables, F, D, and $(PE)_{tr}$, a more confident forecast of the composite curve of the number of transistors per chip versus calendar year can be generated. Figure D-3 unambiguously forecasts a one billion transistor chip by 2000, a projection articulated initially in 1983 (Meindl, 1983). According to the scenario detailed in the preceding discussion and indicated by segment G in Figure D-3, in which the rates of scaling of both minimum feature size and square root of die area are reduced by 50 percent after the 0.125 µm generation, a one trillion transistor chip will be manufactured before 2020. An unusual extension of Figure D-3 can be calculated on the basis of the new complete stochastic frequency distribution for a

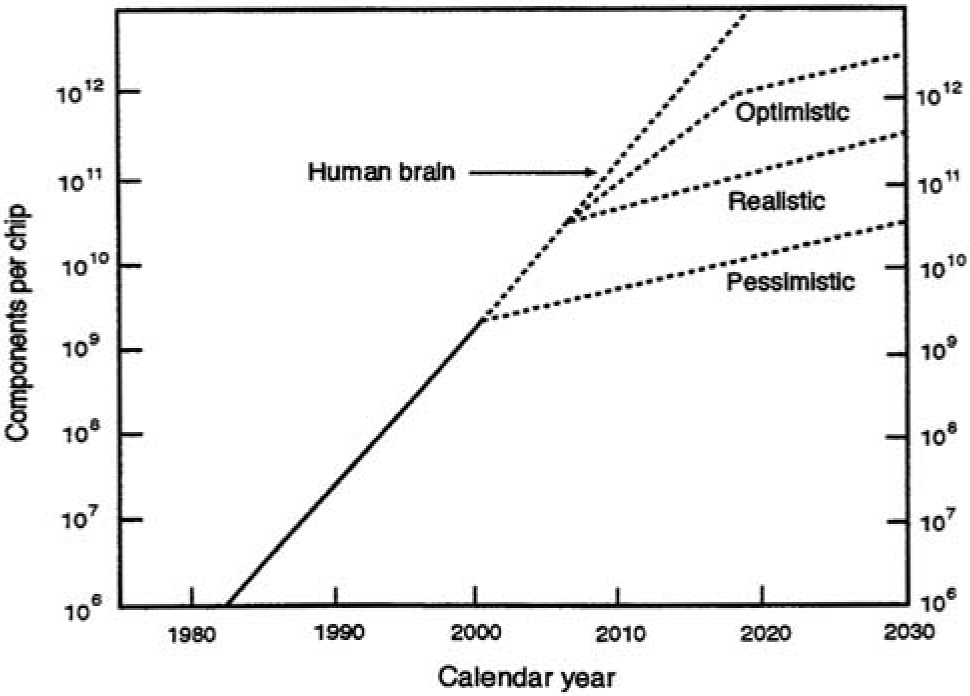


FIGURE D-3 Number of transistors per chip, N_{tr}, versus calendar year, Y.

wiring network, described earlier in the discussion of theoretical system limits. The number of interconnect elements per chip can be expressed as

$$N_{int} = L_{int} / F = FO \,.\, R \,.\, (n_f / n_{tr}) \,.\, N_{tr} \quad (1)$$

where L_{int} is the total length of interconnect per chip, FO is the average fan-out per gate, R is the average interconnect length in gate pitches, n_F is the number of minimum feature lengths per gate pitch, and n_{tr} is the average number of transistors per gate. In this expression, FO, n_F, are relatively constant, R varies slowly with N_{tr}, and, clearly, N_{tr} varies rapidly with calendar year.

A graph of N_{int} versus year is illustrated in Figure D-4 for microprocessor chips. This plot introduces a new metric for GSI, which indicates that the number of interconnect elements per chip for microprocessors and logic now exceeds one billion and is expected to rise to approximately one trillion elements per chip before 2010. A rough rule of thumb at the moment is that the number of interconnect elements per chip is about 50 to 100 times greater than the number of transistors per chip for microprocessor and logic chips.

A remarkable contrast exists between the preceding treatments of theoretical and practical limits on low power GSI. Projections of theoretical limits are based rather solidly on a foundation provided by the laws of physics, as applied to particular materials, devices, circuits, and systems resulting from

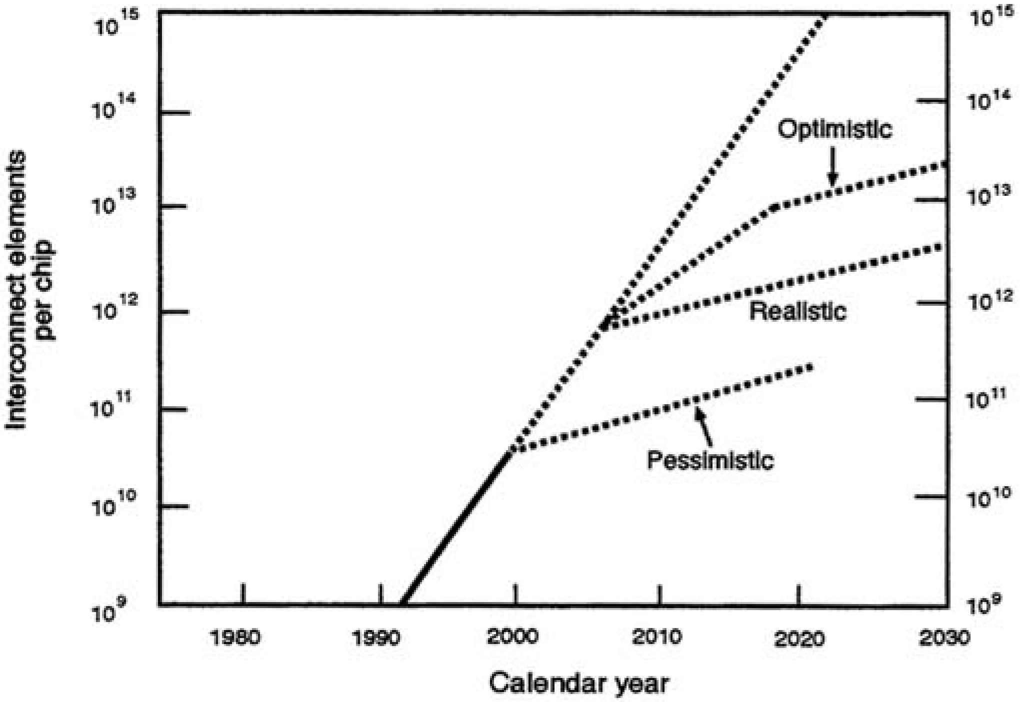


FIGURE D-4 Number of interconnect elements per chip, N_{int}, versus calendar year, Y.

technological innovations and inventions. Consequently, we must anticipate changes in theoretical limits in response to innovations and inventions. But we should also expect accurate forecasts of limits based on assumptions that are reasonable at the time of their engagement. In contrast, practical limits are based largely on empirical experience that cannot be as neatly codified and interpreted as the laws of physics. Although this fact is unlikely to change, it is desirable to seek some way to engage the laws of physics more directly toward improving understanding of practical limits. This is precisely the objective of the following discussion of practical limits that are "intrinsic" to GSI. We seek to define intrinsic or built-in practical limits that are quintessential to the nature of GSI.

It is difficult to imagine another property of GSI that is as intrinsic as the capacity for batch fabrication of billions of transistors and interconnect elements per chip and hundreds of chips per wafer. This capacity for simultaneous manufacturing is the *sine qua non* of microelectronics. Therefore, the singular intrinsic limit that we might choose to be able to define is the number of transistors per chip that is economically viable. The foregoing discussion of practical limits, summarized in Equation (1), clearly implies the myriad of complex factors that combine to determine a viable value for the number of transistors per chip.

What is needed is an approach that somehow reaches beyond this myriad and addresses the intrinsic nature of the problem. This leads to the quest to determine a limit on N_{tr} based on random placement of dopant atoms in a silicon lattice (Keyes, 1975b; De et al., 1996). As a result of both the simultaneous fabrication of many billions of transistors that is inherent to GSI, as well as the presence of many millions of Si lattice sites in the active region of each transistor, the opportunity to designate the placement of a dopant atom at a particular lattice site within each transistor is utterly beyond reach. Consequently, an intrinsic limit on the number of transistors per chip is set by the effects of random placement of dopant atoms in the active channel region of a MOSFET.

The binomial frequency distribution describes the probability of locating a specific number of dopant atoms within a given volume of Si. For a large number of lattice sites, n, within the active region of a MOSFET, and a small probability, p, of site occupancy by a dopant, the average number of dopant atoms per n-sites is given by $\mu = np$, and the standard deviation from this number is $\sigma = (np)^{1/2}$. Assume a MOSFET scaling factor $S > 1$. Calculating the ratio $\sigma/\mu = 1/np$, it becomes clear that—because the number of lattice sites, n, decreases as $S^{-5/2}$ due to scaling down MOSFET dimensions, while the probability of occupancy, p, increases as S due to scaling up doping concentration—the standard deviation relative to the average number of dopant atoms increases as $S^{3/2}$. The result is a larger standard deviation in the distribution of MOSFET parameters, such as threshold voltage and saturation current, as device dimensions scale down. Simultaneously, the number of MOSFETs per chip scales upward. The result of these two abetting increases is a rapidly escalating maximum deviation of MOSFET parameter values for the ensemble of devices within a given chip. At some value of maximum deviation of a MOSFET parameter, for example of V_t, logic circuits will cease to operate without errors.

The approximately ±90-percent maximum deviations in V_t predicted for the NTRS (National Technology Roadmap for Semiconductors) 2010 generation of chips, assuming MOSFETs with uniform channel doping profiles (De et al., 1996), is a rather alarming projection. It indicates strongly that new device structures departing markedly from those that have been the vehicles of scaling over the past two decades must be invented and developed in order to reach the 2010 generation of chips! This is a remarkable insight derived from projecting intrinsic practical limits.

CONCLUSION

What are the critical limits most likely to determine how many billions of transistors we should expect to manufacture in a commercially viable silicon chip? We began with that question. Have we answered it? No—and yes. No, we do not believe that the saturation level of GSI is yet in sight from the perspective of approaching physical limits. Yes, we can look ahead with confidence to another decade of scaling minimum feature size, switching energy, and number of transistors per chip at the exponential rates of the past two decades. From then on, the greatest uncertainty that confronts us is what course microlithography will follow.

The committee believes that a viable new suboptical microlithography technology will be developed, for two principle reasons. First, the principles of physics are not at all discouraging. Second, the economic incentives for doing so are virtually irresistible. The prospects of scaling future species of MOSFETs to 25 nm minimum feature sizes (and perhaps beyond) are promising. Furthermore, between the 25 nm MOSFET and the 0.118 nm tetrahedral radius of a Si atom lie still another two decades of opportunity to scale dimensions, about as much as we have "consumed" so far. Discounting any sub-25 nm breakthroughs, between the 125 nm and the 25 nm generations of chips we can forecast four or five intermediate generations, which should carry us to the trillion transistor chip or terascale integration (TSI).

Therefore, following our anticipated achievement of the 125 nm generation in about a decade, at a rate of three to six years per succeeding generation, we should expect scaling to continue into the 2020 to 2030 time frame. As long as minimum feature size and the number of transistors per chip continue to scale, the advance of low power microelectronics will continue, assuming long interconnects can be largely avoided through new system architectures.

REFERENCES

Bhavnagarwala, A.J., V.K. De, B.L. Austin, and J.D. Meindl. 1996. Circuit techniques for low power CMOS GSI. Pp. 193–196 in Digest of Technical Papers, IEEE International Symposium on Low Power Electronics and Design, Monterey, California, August 11–14. Castine, Maine: John H. Wuorinen.

Chandrakasan, A.P., and R.W. Brodersen. 1995b. Low Power Digital CMOS Design. Norwell, Mass.: Kluwer Academic Publishers.

Davis, J.A., V.K. De, and J.D. Meindl. 1996. Optimum low power interconnect networks. Pp. 78—79 in Digest of Technical Papers, IEEE International Symposium on VLSI Technology, Honolulu, Hawaii, June 10—14. Castine, Maine: John H. Wourinen.

De, V.K., X. Tang, and J.D. Meindl. 1996. Random MOSFET parameter fluctuation limits to gigascale integration. Pp. 198—199 in Digest of Technical Papers, IEEE International Symposium on VLSI Technology, Honolulu, Hawaii, June 10—14. Castine, Maine: John H. Wuorinen.

Keyes, R.W. 1975a. Physical limits in digital electronics. Proceedings of the IEEE 63(5): 740—767.

Keyes, R.W. 1975b. The effect of randomness in the distribution of impurity atoms on FET thresholds . Applied Physics 8: 251—259.

Keyes, R.W. 1979. The evolution of digital electronics towards VLSI. IEEE Journal of Solid State Circuits 14(2): 193—201.

Kung, H.T. 1982. Why systolic architectures?. IEEE Computer 15(1): 37—47.

Meindl, J.D. 1983. Theoretical, practical and analogical limits in ULSI. Pp. 8—13 in Digest of Technical Papers, IEEE International Electronic Devices Meeting, December. Castine, Maine: John H. Wourinen.

Meindl, J.D. 1995. Low power microelectronics: Retrospect and prospect. Proceedings of the IEEE 83(4): 619—635.

Meindl, J.D. 1996. Gigascale integration: is the sky the limit?. IEEE Circuits and Devices 12(November): 19—24, 32.

Ohmi, T. 1994. Scientific semiconductor manufacturing based on ultra clean processing concept. Pp. 3—22 in Proceedings of the International Conference on Advanced Microelectronic Devices and Processing, Sendai, Japan, February 28–March 4. Sendai: Tohoku University.

Sai-Halasz, G.A. 1995. Performance trends in high-end processors. Proceedings of the IEEE 83(1): 20—36.

SIA (Semiconductor Industry Association). 1994. The National Technology Roadmap for Semiconductors. San Jose, Calif.: Semiconductor Industry Association. Updated version to be published in fall 1997.

Appendix E

Wearable Speech-Operated Computer

Figure E-1 depicts the evolution of a speech-operated system implemented in software from a standard laptop computer to a belt-worn computer to a hand-held device. The effectiveness of the design is measured by a figure of merit defined by real time response divided by the volume multiplied by the weight and the power normalized to unity for the laptop. As described in this appendix, the effectiveness of the system was improved by almost three orders of magnitude by improving volume, weight, and power consumption by at least a factor of five.

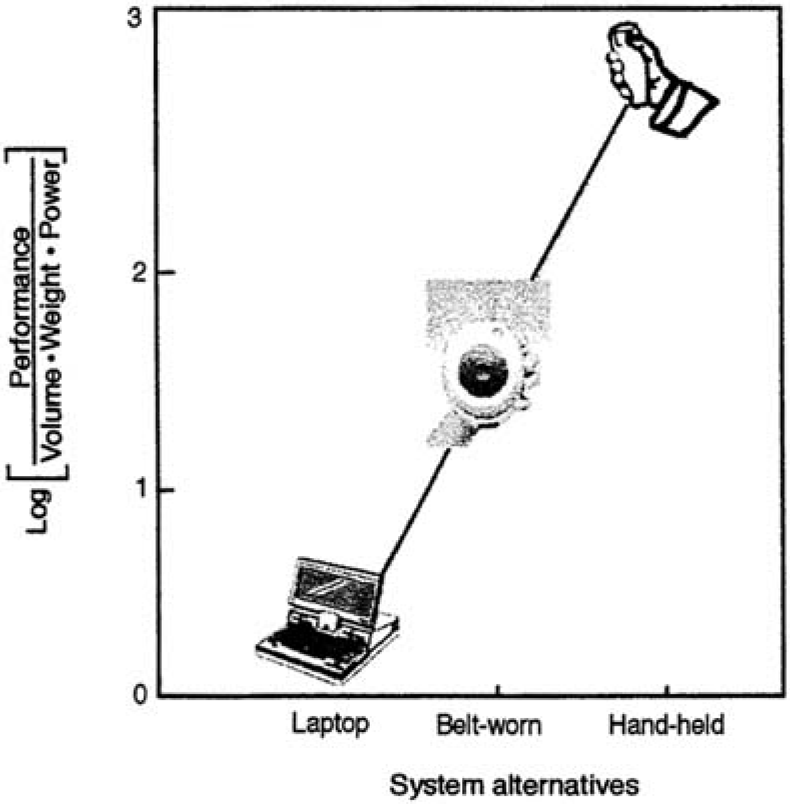


FIGURE E-1 Composite performance of speech-operated systems.

Figure E-2 depicts two systems and shows the impact of power management techniques. Navigator 1 was a first generation design for a speech-operated system and was based on an Intel 80386, 25 MHz processor with 16 MBytes of main memory and an 85 MByte disk drive. The system was controlled by speech recognition software. Once the basic hardware configuration was selected, the energy usage of the system was reduced by more than a factor of two using the following techniques:

- Operating system software. A profile of computer usage revealed that the system never took advantage of a low energy-consuming standby mode of operation. Further examination indicated that even when the system was idle the operating system was making more than 150 different types of calls to system utilities that consumed energy, not only in the processor but also in the peripheral devices, such as the hard disk drive by keeping it actively spinning. By replacing the functionality of the old idle loop with a halt instruction, the processor was able to enter standby mode and save more than a factor of two in energy consumption.
- Hard disk drive. The disk drive was placed in standby mode when it was not required for loading programs.
- Application profile. The speech-driven application was profiled to determine which system resources were consumed. A number of peripheral buses and input/output ports were not required. These digital signals were terminated by energy consuming resistors. Thus, substantial energy was saved by permanently disabling resources that were not used by the application. In addition, the power supply was redesigned to increase efficiency when delivering multiple voltages from the battery subsystem.

In the second generation system, called Navigator 2, a hardware system consisting of an Intel 80486 processor operating at 33 MHz with 12 MBytes of main storage and a 420 MByte disk drive was used. The system was designed for use during the inspection of sheet metal on aircraft. The following techniques cut energy consumption of the basic hardware system by a factor of four:

- Processor clock frequency. The processor clock frequency was lowered to the minimum that could provide an adequate response for the application. Rather than seeking a software speech recognition solution that would have required at least 100 MIPS (as was done in Navigator 1), a separate dedicated speech application PCMCIA card, based upon a 13 Mhz DSP, allowed the selection of a more energy-efficient processor.

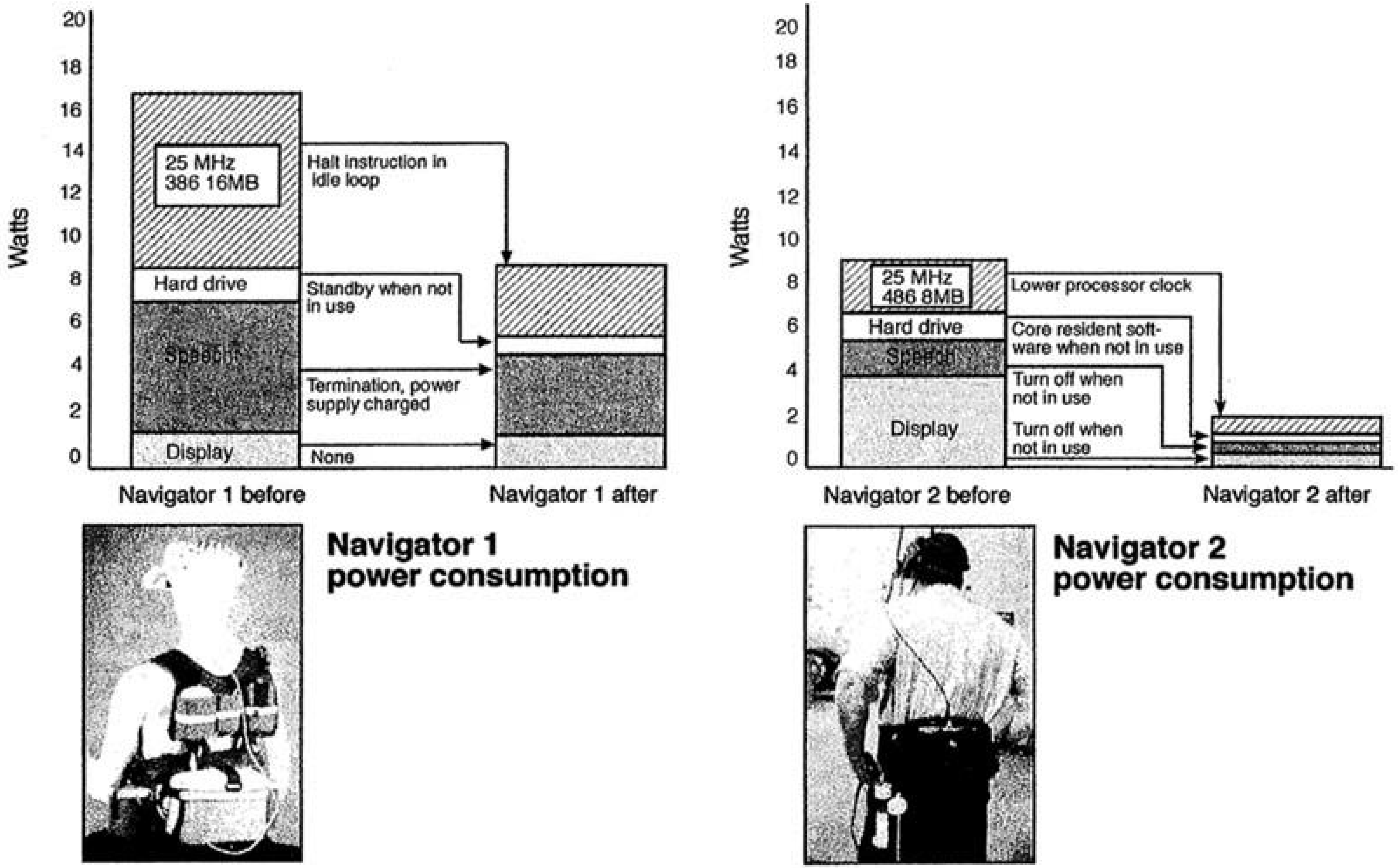


FIGURE E-2 Impact of power management on wearable computers.

- Hard disk drive. The software was modified to be core-resident to avoid paging from the hard drive. Thus the hard drive could be disabled except for program loading and database updates.
- Speech. A separate "onset of speech" recognition circuit enabled the speech recognition PCMCIA card only when there was actual speech to be recognized. Otherwise the speech recognition card was disabled.
- Display. The display was disabled when it was moved from in front of the eyes or after a period of inactivity. The "see-through" display allowed viewing of the user's environment without physically removing the display.

Power reductions made over the two generations of the Navigator speech-operated system are examples of what can be accomplished using standard PC hardware by moving from general-purpose operation to function-specific operation. Much greater improvements, by factors of 10 to 100, can be achieved by moving away from PC hardware platforms to dedicated embedded systems.