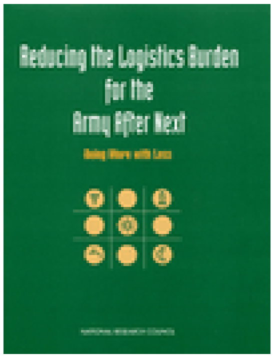

Reducing the Logistics Burden for the Army After Next: Doing More with Less

Committee to Perform a Technology Assessment Focused on Logistics Support Requirements for Future Army Combat Systems, National Research Council

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Doing More with Less

Committee to Perform a Technology Assessment Focused on Logistics Support Requirements for Future Army Combat Systems
Board on Army Science and Technology
Commission on Engineering and Technical Systems
National Research Council

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Preface

This study lays out steps that should be taken for the Army to field combat systems with reduced logistics support requirements for a highly mobile and lethal battle force that is fundamentally self-sufficient. Although the study is based on a notional battle force concept provided by the Army to illustrate possibilities and alternatives, the findings also can be applied to the development of systems for other missions. Reductions in logistics demand that can be achieved by addressing logistical implications during system design will be more significant than improving the ways that logistics support is provided.

The study provides a road map for research and technology development based on logistical considerations and offers a unique perspective on ideas and technologies currently being considered by the Army. The committee believes that current technology can be adapted to support the incorporation of logistical considerations in planning to a degree not previously imagined. Clearly, attention to logistics trade-off analysis is absolutely essential for the Army to get the most "bang for its buck" by 2025. For perhaps the first time, the Army has both an opportunity *and the technology* to consider fully the logistical implications in designing a force. Recognizing the likely threats and required capabilities, the Army has every reason to do so.

The scope and complexity of issues surrounding the AAN are challenging. The committee relied heavily on the Army for information on conceptual requirements and on the status of research activities. We appreciate very much the willingness of everyone involved to provide background data and to discuss issues candidly.

GERALD E. GALLOWAY, JR., CHAIR

COMMITTEE TO PERFORM A TECHNOLOGY ASSESSMENT FOCUSED ON LOGISTICS SUPPORT REQUIREMENTS FOR FUTURE ARMY COMBAT SYSTEMS

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

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While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the National Research Council.

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Acronyms and Abbreviations

ACRONYMS

AAN	Army After Next
AFSS	advanced fire support system
AMC	Army Materiel Command
AMSAA	Army Materiel Systems Analysis Activity
ARL	Army Research Laboratory
ARO	Amy Research Office
ATACMS	Army tactical missile system
ATM	asynchronous transfer mode
ATR	automated target recognition
BAT	brilliant anti-tank
BUSE	battle unit support element
BVRAAM	beyond visual range air-to-air missile
C3I	command, control, communications, and intelligence
C4ISR	command and control, communications, computers, intelligence, surveillance, and reconnaissance
CAE	computer-aided engineering
CAV	composite armored vehicle
CBW	chemical/biological warfare
CECOM	Communications-Electronic Command Center
CKEM	compact kinetic energy missile
CMOS	complementary-metal oxide on silicon
CNP	compact nuclear power
CNPS	compact nuclear power source
CRAF	Civilian Reserve Air Fleet Program
DARPA	Defense Advanced Research Projects Agency
DEW	directed energy warfare
DIS	distributed interactive simulation
DOC	Department of Commerce
DoD	Department of Defense
EM	electromagnetic
EMP	electromagnetic pulse
ETC	electrothermal chemical

FCS	Future Combat System
FEL	free electron lasers
FLIR	forward-looking infrared
FSCS	future scout and cavalry system
GIRAS	gas-inflated ram air stabilizer
GPS	global positioning system
GS	general support
HLA	high level architecture
HMMWV	high mobility multipurpose wheeled vehicles
HMX	high melting explosive
HPM	high power microwaves
HPMM	high power millimeter wave
IAT	Institute for Advanced Technology
IC	integrated circuit
IDA	Institute for Defense Analysis
IHPRPT	Integrated High Payoff Rocket Propulsion Technology
IFF	identification of friend or foe
IR	infrared
JCS	Joint Chiefs of Staff
JRP	Joint Robotics Program
KEP	kinetic energy penetrator
LMSR	large, medium-speed, roll-on/roll-off
LRP	long rod penetrator
LTL	less than lethal
M&S	modeling and simulation
MRE	meals ready-to-eat
MLRS	multiple launch rocket systems
NATO	North Atlantic Treaty Organization
NIMA	National Imagery and Mapping Agency
NRC	National Research Council
NRMM	NATO Reference Mobility Model
NRO	National Reconnaissance Office
NSA	National Security Agency
PBX	plastic-bonded explosive
PEM	proton exchange membrane
PNGV	Partnership for a New Generation of Vehicles
POL	(petrol, oil, lubricants) petroleum
QWIP	quantum-well infrared photodetector
RAMD	reliability, availability, maintainability, and durability
RDEC	research, development engineering center

RDT&E	research, development, testing and evaluation
RDX	rapid detonating explosive
RHA	rolled homogeneous armor
RML	Revolution in Military Logistics
RSTA	reconnaissance, surveillance, target acquisition
S&T	science and technology
SA	situational awareness
SGE	surface ground-effect
SRO	strategic research objective
STO	science and technology objective
TARDEC	Tank Automotive Research Development and Engineering Center
TE	thermoelectric
TOE	table of organization and equipment
TRADOC	Army Training and Doctrine Command
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
UGVTEE	UGV Technology Enhancement and Exploitation
UUV	unmanned undersea vehicles
VEHDYN	vehicle dynamics subsystem
WES	Waterways Experiment Station
WIG	wing-in-ground
cm^3	cubic centimeter
Ft-lb	foot pound
KE	kinetic energy
kg	kilogram
kW·h	kilowatt hour
km/h	kilometer hour
kW	kilowatt
MW	megawatt
MW·h	megawatt hour
mJ	millijoule
nm	nanometer

Executive Summary

This study assesses the potential of new technology to reduce logistics support requirements for future Army combat systems. It describes and recommends areas of research and technology development in which the Army should invest now to field systems that will reduce logistics burdens and provide desired capabilities for an "Army After Next (AAN) battle force" in 2025. In requesting this study, the Army asked the National Research Council (NRC) to undertake the following tasks:

- Understand the importance of logistical considerations to successful battlefield operations and the likely impact of different enabling technologies on logistics support.
- Review concepts under consideration for soldier and battlefield systems for the AAN time frame.
- Analyze enabling technologies on which capabilities contemplated for the AAN will depend, and propose alternative technologies that would reduce the need for logistics support.
- Identify and evaluate areas of research that would reduce the logistics requirements for systems and operational concepts in the 2025 time frame of the AAN.
- Develop specific recommendations for the Army's science and technology (S&T) investment strategy, including research objectives and a road map for achieving them.

The NRC established the Committee to Perform a Technology Assessment Focused on Logistics Support Requirements for Future Army Combat Systems to complete these tasks.

LOGISTICS AND THE ARMY AFTER NEXT

The activities required to transport and sustain a military force, collectively known as logistics, are central to success on the battlefield. The Army envisions that by 2025 it should be capable of rapidly inserting a highly effective battle force (referred to as the AAN battle force) practically anywhere on Earth to engage an enemy in any environment, including an urban center. Combat systems used by the battle force would require only a minimum of logistics support. The AAN battle force would be followed by conventional forces (requiring much more time to deploy and substantially more logistics support) only if necessary.

Combat forces have traditionally depended on a logistics "tail" of combat support and service support units to transport supplies, maintain systems, and provide food, water, and medical support. The AAN battle force, however, will be self-sustaining for up to 14 days. It must have the unprecedented operational and tactical mobility to move up to 1,000 km from a staging area and engage an enemy force at speeds averaging 200 km/h.

The committee determined that the logistics burdens of fuel and ammunition would overshadow all other logistics demands of the battle force. Burden reduction goals identified include: reducing fuel demand; increasing fuel energy density; improving energy systems and energy management; reducing the weight of vehicles and ammunition; reducing the number of rounds per target; increasing system reliability; lightening soldier systems and increasing soldier effectiveness; and optimizing system designs.

ANALYSIS OF TECHNOLOGY APPLICATIONS

The broad functional categories of *operational and tactical mobility* and *combat engagement* were used throughout the study for the committee's analysis and discussion of burden-reducing technologies. Two other groupings of burden-reducing technologies—technologies to reduce *fuel and energy* and technologies to improve the *reliability* of combat systems—emerged from analyses of the technologies involved in the sustainment of combat systems.

A fifth technology category, modeling and simulation tools to support *logistics trade-off analysis,* emerged during the committee's investigation of mobility requirements and was considered to play an essential role in elevating logistical considerations to the same level as other performance factors in the design and acquisition of AAN combat systems. Unless major improvements are made in the Army's capability to model the logistics demands of systems while they are still in the concept stage and to quantify the impact of technological and design alternatives on those demands, logistics support requirements will probably not be reduced or even held to present-day levels.

General themes that emerged from the assessment of each of the five functional technology categories are discussed below. Recommendations on technology development and research needed to meet the burden reduction goals follow in the section on Road Map Objectives for Research and Technology Development.

Logistics Trade-off Analysis

To achieve substantial reductions in logistics burdens, new AAN systems will require that systems engineering trade-off studies be performed before design decisions are made. Given limited resources, M&S tools are the only known means of conducting the requisite analyses in time (by 2010 for AAN systems to be fielded by 2025). However, the existing M&S tools are largely inadequate for making quantitative comparisons and system performance trade-offs. Significant improvements and extensions of M&S capabilities will be necessary, particularly for modeling logistics demands under AAN battle force operating scenarios. Ideally, extensions to existing capabilities will become part of a distributed M&S environment that can be used for multiple purposes in support of AAN systems.

Fuel and Energy

Fuel is stored energy. To decrease the logistics burden of fuel, either energy can be supplied in a more compact form (less tonnage and transport volume) or the battle force's demand for energy can be reduced. The committee studied a *high-risk,* but potentially high-payoff, alternative to the current energy supply system based on petroleum fuels. Portable nuclear power plants at the staging area could be used to produce electricity, which could be used to electrolyze locally obtained water to produce hydrogen. Assuming safe storage and distribution mechanisms are developed, hydrogen could become the primary battlefield fuel. The assessment of this risk-laden alternative, which is unlikely to be ready for implementation before 2025, illustrates the importance of being able to evaluate the entire fuel supply and demand structure *as a system* to achieve logistics savings.

A more certain approach to reducing the fuel burden is to *reduce energy demand,* principally by reducing the weight of AAN combat vehicles. For this, vehicle developers will need better information about lighter weight alternatives to conventional materials and design approaches. Innovative materials and structural components must be sought to reduce overall system weight without compromising other system requirements. Fuel demand can also be reduced by better management of vehicles as energy systems and by requiring that vehicle developers meet elemental system-level fuel consumption specifications.

To reduce the energy demand of combat vehicles, survivability and lethality capabilities will have to be improved. Fuel requirements of the AAN battle force will be profoundly affected by how the combat vehicle is used on the battlefield. The Army will have to decide whether equipping a vehicle both to fire kinetic-energy penetrating (KEP) projectiles and to withstand KEP hits is worth the additional weight. Once desired capabilities are determined, the duty cycles for the vehicles will have to be modeled to determine whether alternative concepts, such as a hybrid-electric engine, can reduce overall energy consumption.

Operational and Tactical Mobility

Operational mobility for AAN means transporting a battle force from the staging area to the area of operations, or battle space. The tiltrotor and rotary-wing transporters under development can only meet AAN objectives for operational mobility with an extremely large number of transporters and an immense fuel burden. Tactical mobility will have to depend on ground-traction vehicles (e.g., moving on wheels or tracks) unless novel concepts for off-the-ground mobility can be developed. Off-the-ground concepts could also provide a fuel-efficient option for operational mobility.

The surest way to meet the combination of high cross-country mobility and reduced weight desired for tactical mobility would be a family of wheeled vehicles with advanced technology for active suspension, look-ahead terrain awareness, and subsystem automation to reduce crew size. A distributed, hierarchical M&S environment that can model mobility system and technology alternatives will be essential for the Army to make rational choices about AAN mobility systems.

Combat Engagement

AAN battle force engagement systems will be dependent on situational awareness (SA) technologies (the same technologies used for command, control, communications, computing, intelligence, surveillance, and reconnaissance [C4ISR] functions) and on lethal weapon mechanisms, either projectile or directed energy systems. The effectiveness of these engagement systems will depend on near-perfect SA. Given the dynamic pace and short life cycle of SA technologies, the committee is concerned about the increasing vulnerability of Army combat systems to "technology overmatch."

Technologies that ensure that every round fired is effective against its target will have the greatest impact on the ammunition logistics burden, as well as providing formidable lethal effectiveness for an AAN battle force. Improved precision guidance and increased lethality are thus key performance objectives for projectile weapon systems. Directed energy weapons may have antisensor and anti-SA applications in the AAN timeframe, but they should complement rather than replace projectile weapons and their associated ammunition burdens.

Reliability Concepts

Improved system reliability will have a multiplier effect on reducing logistics burdens. For reliability (and related concepts, such as availability or maintainability) to be engineered into AAN system designs and retained during system optimization, objective, quantifiable measures for these system-level characteristics must be derived from operational requirements. The term "ultrareliability" is misleading unless it can be defined in the context of likely AAN operations (for example, duty cycles for typical missions). Performance measures that incorporate reliability requirements can be defined for each functional or structural level of the design hierarchy, from mission reliability to system and subsystem reliability, all the way down to the properties of the materials selected or designed for components. A distributed M&S environment can be used to design reliability into AAN systems, if validated data on desired and achievable reliability-related characteristics can flow up and down a functional and structural hierarchy of M&S tools. Because system failures cannot usually be attributed to a single cause, reliability models will be necessary at all levels of the hierarchy.

SOLDIER SUSTAINMENT

Increasing the combat effectiveness of soldiers by meeting soldier-level logistics requirements will be as important as reducing logistics support requirements for vehicles and weapons systems. The soldier's logistics support requirements cannot be addressed by focusing on the total weight (tonnage) and transport volume of provisions and supplies. Increases in the range, speed, and variety of AAN operations will require that physical loads borne by soldiers be reduced dramatically. Soldiers will require compact power supplies; lightweight and nonrestrictive protection from ballistic, chemical, and biological threats; and improved physical and mental fitness through preventive medicine and nutrition.

JOINT FORCE REQUIREMENTS

The committee identified areas of research and technology development important for reducing AAN logistics demand that should be joint programs with the other military services or conducted through agencies of the U.S. Department of Defense (DoD). The Army will depend on the Air Force and Navy to ferry the battle force and sustaining supplies to the staging area, to provide coordinated fire support, and to assist with C4ISR. Therefore, the Army should participate in planning for this support to ensure that AAN operational and logistical needs are met.

Technology developments necessary to enable strategic lift of the battle force will overlap with the technology requirements for operational, and possibly tactical, mobility. The Army should identify the overlapping requirements and encourage DoD to establish responsibilities as soon as possible among the services for satisfying these requirements.

CHANGING PATTERNS IN TECHNOLOGY INNOVATION

The rapid growth and global competition in commercial markets for complex technological products, coupled with decreases in defense spending, are challenging the role DoD has played since World War II in determining the direction of product development, although DoD is still the principal sponsor of high-risk, innovative research at universities and federal laboratories. In their roles as consumers of technology, DoD and the Army must take full advantage of cooperative endeavors involving industry, academia, and the other services. The committee's recommendations for research and technology investment adhere to the principle that Army dollars should be invested primarily in projects that address Army-specific requirements or projects that would not be undertaken without Army support. The committee also reviewed and commented on several aspects of the current Strategic Research Objectives included in the Army S&T program.

ROAD MAP OBJECTIVES FOR RESEARCH AND TECHNOLOGY DEVELOPMENT

Table ES-1 summarizes the committee's findings on the research and technology areas to reduce AAN logistics burdens. *Road map objectives* in the middle column provide feasible routes to meeting the logistics burden reduction goals, listed in the second column. The two right-hand columns list the specific areas of technology development and research (basic or applied) that will be essential to achieving each road map objective.

Distributed M&S environments are an essential technology for several of the road map objectives. M&S tools are needed to support systems design and trade-off analyses to weigh logistics demands equally with other performance objectives.

TABLE ES-1 Logistics Burdens, Burden Reduction Goals, Road Map Objectives, Technology Development Areas, and Research Areas

Logistics Burden	Burden Reduction Goal	Road Map Objective	Technology Development Area	Research Area
Fuel (weight and/or volume)	Reduce fuel and energy demand	Lightweight materials for air and ground vehicles	Distributed M&S[a] environment Materials selection databases and information resources	M&S for materials design Advanced armor and protection concepts
		Airframe weight; engine design	Distributed M&S environment	Novel air mobility concepts
		Minimally crewed vehicles	Distributed M&S environment Subsystem automation	Robotics
	Improve system energy management	Mobility systems evaluation	Distributed M&S environment (mobility systems) Fuel-economy specifications Driver training Hybrid vehicles evaluation	Active suspension
		Terrain awareness	Look-ahead sensors and systems Mobility models	Terrain sensor concepts
	Increase fuel energy density by weight	New energy delivery systems	Energy system modeling Compact nuclear power	Hydrogen storage
	Reduce lethal system weight	Lethal systems performance	Distributed M&S environment (lethal systems)	
Ammunition (weight and/or volume)	Reduce rounds per target	Situational awareness	Communications, sensor, and decision support systems; data integration and filtering Unmanned aerial vehicle and unmanned ground vehicle systems	C4ISR[b] supportability and robustness Artificial intelligence, robotics
		Precision guidance	Affordable small integrated guidance systems	Improved sensors, onboard processors, packaging, and controls

		Lethal systems performance	Distributed M&S environment (lethal systems)	
	Reduce weight per round	Energetics and warhead materials	Warhead materials M&S, evaluation Insensitive munitions	Advanced energetic formulations Insensitive energetics
		Lethal systems performance	Distributed M&S environment (lethal systems)	
Maintenance (refitting and repair)	Improve system reliability	Systems design for reliability	Distributed M&S environment with reliability metrics Materials selection databases and information resources	M&S of materials for application-specific reliability
Spare parts (weight and/or volume)	Improve system reliability	Systems design for reliability	Distributed M&S environment with reliability metrics Materials selection information resources	M&S of materials for application-specific reliability
Soldier systems and sustainment (weight)	Lighten soldier load	Compact power	Systems engineering of power demand	Microelectromechanical systems Nuclear batteries
		Lightweight protection systems (armor, chemical and biological agents, radiation)	Integrated protective garments and shielding	Novel materials
	Increase soldier effectiveness	Medical, nutrition, fitness	Life support systems	Nutrition; physical and mental augmentation concepts
All of the above	Optimize systems	AAN logistics trade-off analysis	Distributed M&S environment	
Inefficient logistics	"Just-right" logistics	Logistics situational awareness	Logistics command and control	C4ISR supportability and robustness

[a]Modeling and simulation
[b]Command, control, communications, computers, intelligence, surveillance, and reconnaissance

Although the Army and DoD have already invested a good deal in M&S tools, these tools will have to be significantly extended and enhanced to support logistics trade-off analyses.

There are three reasons for this. First, existing tools do not enable realistic, quantitative modeling of the logistics demands associated with the operating conditions being modeled. Second, even in an application area such as ground mobility, where many tools already exist, results from one level of modeling cannot be used as input to models at another structural level. These functional and structural levels ought to form a simulation hierarchy extending from high-level simulations of force-on-force engagements down to engineering models of individual systems, subsystems, and components. The capability to link input data and results among tools at different levels in this hierarchy is essential for the iterated testing and assessment of logistics demands in relation to other performance characteristics, before major system decisions are made. Third, even in functional areas where the Army and other agencies have a range of active research and development programs—such as projectile weapon technologies—these programs are not producing the data on logistics demand necessary to analyze performance trade-offs.

Reducing the Fuel Burden

Substituting *lightweight materials* with equivalent or superior functionality in designs for air and ground vehicles is the most promising approach for reducing total system weight. The committee identified vehicle system weight as the most important factor in reducing AAN fuel demand. Careful systems-level evaluations will be necessary to make these substitutions, but designers are often constrained by a lack of information on nontraditional alternative materials. Adequate information resources to support materials selection must accompany the development of M&S technology. The two areas of research that would be most valuable for meeting this objective are (1) research on multifunctional materials that provide superior performance for protection and structural functions while reducing system weight, and (2) the use of M&S research tools to design new microstructured versions of materials and the processing techniques to manufacture them efficiently.

The committee concluded that the Army lacks an affordable concept for transporting the battle force to the battle area from a staging area. The road map objective of *airborne systems with lighter airframes and light, fuel-efficient engines* is intended to meet this operational mobility requirement with minimal logistics support requirements. The committee also found no technology development candidates, consistent with fuel demand reduction goals for an airborne platform that could serve as the principal vehicle to enable tactical mobility for the battle force. To realize the AAN vision of a battle force maneuvering in a three-dimensional battle space at speeds several times faster than the speed of current ground forces but with reduced fuel demand, the Army must look for novel mobility concepts, such as surface ground-effects vehicles. If the necessary basic and applied research does produce promising candidates, a distributed M&S environment that can model logistics demands for air and ground mobility systems will be essential for designing and developing battle-competent systems within the AAN time frame.

Minimally crewed vehicles could decrease vehicle weight, although the trade-offs among fuel demand and other performance objectives will require the kind of quantitative analysis that only a distributed M&S environment could provide. In the long-term, unmanned ground vehicles might be effective as components of a squad that includes human commanders in some squad vehicles. Research in robotics, artificial intelligence and related areas (primarily control theory) would support this road map objective.

The *mobility systems evaluation* objective in Table ES-1 refers to the need for total systems evaluations of the many technology options for AAN ground vehicles. Technologies such as hybrid drive, intelligent engines, active suspension, terrain sensors, and energy storage and recovery should be incorporated into system designs and evaluated for their impact on fuel consumption and other logistics burdens in scenarios typical of AAN missions. A straightforward way to force the innovative use of technologies to reduce fuel consumption is to include specific constraints on fuel consumption as a functional specification for a system, thereby requiring interested developers to engineer a competitive integration of technologies.

New energy delivery systems could increase the amount of fuel energy delivered per unit of transported weight and volume. A fuel supply model that can be realistically coupled with models of fuel demand for AAN system concepts being evaluated in war games is needed as soon as possible. This modeling capability should be adaptable for use in trade-off analyses for improving fuel systems, mission planning, and training exercises that include realistic logistics constraints. It will also be essential for evaluating radical innovations, such as the high-risk, high-payoff possibility of coupling a modular nuclear reactor located at the AAN staging area with conversion to hydrogen as the primary battlefield fuel.

Some of the technologies being developed for improving *lethal systems performance* could reduce ammunition weight while increasing fuel demand, either by replacing propellant with fuel as an energy source or by moving a heavier system around the tactical battle space. The committee found no evidence that these implicit trade-offs have been acknowledged, much less analyzed systematically. The associated burden reduction goal of "reducing lethal system weight" is a reminder that weight is a common factor in reducing fuel demands for *all* AAN combat systems and subsystems.

Reducing the Ammunition Burden

The committee found that *situational awareness* technologies and underlying research on alternative lethal systems and *precision-guided munitions* have the most potential to reduce the ammunition logistics burden. Many of the electronics, electro-optical, and data processing technologies used in SA applications are also relevant to compact, affordable, integrated guidance systems for missiles and munitions. Continued research in command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) supportability and robustness is imperative because any loss or degradation in the near-perfect SA that the Army will require for successful battle force engagements could have cascading consequences.

Reducing the rounds required per target depends on improving the precision of projectile propulsion systems. The committee found little data from the ongoing development programs that would be useful for making quantitative comparisons among alternative systems on this aspect of performance. *Energetics,* materials with high energy density, and improved *warhead materials* for projectiles can reduce the weight per round for a projectile weapon system, as can less sensitive munitions. The committee found that the best opportunities for reducing weight per round are in improving the performance of an energetic as a propellant or explosive while decreasing its sensitivity to heat or shock during transport, storage, and handling.

Reducing Other Burdens

Systems design for reliability depends on incorporating reliability-related metrics into the distributed M&S environments used to analyze the logistics demands of candidate designs and to make trade-offs with other performance objectives. At the lower levels of the structural hierarchy, the materials and substructure properties that contribute to overall system reliability should be identified, and materials selection should be based on those properties, in addition to other performance-related properties. The committee also foresees a long-term research requirement for modeling innovative material structures and the processes for producing and fabricating them efficiently, so that future Army combat systems can meet operational reliability requirements, use lighter materials to reduce total system weight, and still achieve superior combat effectiveness.

In keeping with its Statement of Task, the committee focused on technologies to reduce logistics demands of combat systems and did not study technologies to improve logistics systems; however, the table includes an entry for technologies and research to support *logistics SA* to emphasize the ubiquitous role of SA technologies in the AAN time frame.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

In addition to detailed findings and recommendations on research and technology development in which the Army should invest, the committee formulated general conclusions about reducing logistics support requirements for Army After Next systems. Each conclusion is followed by one or more recommendations.

Conclusion 1. The Army can reduce logistics demand for Army After Next combat systems.

Fuel and ammunition will continue to be the dominant logistics burdens of an AAN battle force. Investments in research and technology development can achieve specific burden reduction goals. Reducing or eliminating the demand for fuel, ammunition, and spare parts will have a ripple effect by reducing the need for separate logistics units and personnel to support the battle force.

The primary ways to reduce logistics demand for fuel and ammunition include research and technology developments in modeling and simulation, lightweight vehicles and systems, and improved precision guidance systems. The demand for spare parts and maintenance support can be reduced by including reliability as a performance requirement at all levels of system design.

Recommendation 1. The Army should invest in the research and technology development areas listed in the last two columns of Table ES-1 to reduce logistics demand for Army After Next systems.

Conclusion 2. Technologies for improving situational awareness (SA) are critical to reducing logistics demands for AAN systems. SA is essential for fuel-efficient, high-speed mobility and for engaging targets efficiently and effectively, thereby reducing battlefield requirements for both fuel and ammunition. AAN systems will be even more dependent on SA technologies than those developed for Army XXI.

Recommendation 2. The Army should assume that currently contemplated standards of command, control, communications, computing, intelligence, surveillance, and reconnaissance (C4ISR) will not be adequate to support the near-perfect situational awareness requirements of an Army After Next battle force. The Army should ensure adequate funding for research and development of secure, robust, and supportable C4ISR systems and should adapt new information technologies to meet Army After Next requirements as they are identified.

Conclusion 3. The development of joint-service capabilities will affect the Army's ability to reduce AAN logistics burdens. Because future operational concepts for the Army and the other services will be derived from the DoD *Joint Vision 2010,* the AAN should be planned to take full advantage of research and technology developments sponsored by DoD and the other services.

Promising commercial programs are under way in both heavy-lift aircraft and high-speed ships that might provide the AAN with unprecedented strategic mobility from the continental United States to forward staging areas and, by 2025, perhaps even into the battle area. If the Air Force and Navy adopt new aircraft and ships, strategic lift capabilities provided to the AAN battle force and follow-on forces would be significantly improved.

Prospective enhancements in C4ISR and weapons systems developed by the other services can be integrated into AAN planning, thereby reducing the need for deploying parallel capabilities. Technologies developed to support SA and force projection for the other services might also be used for AAN systems.

Recommendation 3a. The Army should work to influence commercial developments in strategic mobility to ensure that new capabilities include military add-ons to the commercial designs. The Army should participate in design reviews with commercial developers to ensure that battle force requirements are met. (A similar approach was recommended in *STAR 21: Strategic Technologies for the Army of the Twenty-First Century.)*

Recommendation 3b. The Army should integrate the situational awareness and fire support capabilities of the other services into the Army After Next concept.

Conclusion 4. Revolutionary changes in battlefield mobility for an AAN battle force are unlikely to be attained before 2025. The committee found no combination of technologies that would be capable of simultaneously meeting hypothesized requirements for speed, weight, fuel consumption, survivability, and lethality for AAN fighting vehicles.

Current concepts for meeting AAN operational and tactical mobility goals do not provide for the desired increases in mobility or reductions in fuel consumption. The committee estimates that a future 15-ton wheeled combat vehicle able to attain cross-country speeds of up to 130 km/h over moderate terrain is technically feasible. Air carriers capable of meeting operational lift requirements for a force of 15-ton vehicles are also technically feasible, but these carriers may not be affordable and would add significantly to the overall fuel burden.

Recommendation 4a. If the Army After Next battle force requires a capability for cross-country mobility at speeds of more than 130 km/h, the Army will have to develop novel mobility alternatives. Research in novel technology areas, such as surface ground effects, will only be undertaken at the Army's insistence and should begin immediately.

Recommendation 4b. If 130-km/h cross-country mobility is adequate for Army After Next operations, the Army should develop requirements for a family of minimally crewed wheeled vehicles to perform battlefield functions.

Recommendation 4c. The Army should define its long-term requirements for operational and tactical mobility and work with the U.S. Department of Defense to clarify joint-service responsibilities. Research and technology development should be pursued on a department-wide basis to fulfill overlapping objectives of the Army and other services for the AAN time frame.

Conclusion 5. Reliability considerations (including reliability, availability, maintainability, and durability) have been routinely sacrificed for other performance characteristics. To reduce logistics demand for AAN systems, reliability must be treated on an equal basis with lethality, survivability, and mobility in the design process.

Recommendation 5. The Army should revise its design and source selection criteria for battle force systems so that reliability is considered on an equal basis with other mission-specific goals.

Conclusion 6. Logistics support for soldiers requires special attention because the individual soldier will be the most essential combat system in the Army After Next.

Advances that extend human physical capacity and reduce the need for medical support could lead to quantum improvements in soldier combat performance. Reducing the soldier's logistics support requirements would have a multiplier effect by increasing combat effectiveness and reducing logistics demand for medical support, water, food, and life support.

Recommendation 6. The Army should focus on the "soldier as a system" by ensuring adequate funding for research and technology developments to reduce the weight and bulk of the soldier's combat load and to extend the soldier's physiological and psychological capacities.

Conclusion 7. Technology solutions to reduce the logistics demands of Army After Next systems will not be simple.

The committee does not foresee breakthroughs in technology that will alter fundamental logistical considerations by 2025 for an AAN battle force. Therefore, the Army should apply technology directly toward achieving specific burden reduction goals rather than anticipating that a magic substitute for fuel or ammunition will be found.

The AAN shift away from heavy direct-engagement systems toward smaller, more versatile platforms capable of operating in diverse environments, including urban centers, will reduce the Army's traditional dependence on a "supply line" to meet fuel and ammunition requirements and will reduce the numbers of both combat and logistics personnel *in the battle area.* The dramatic improvements in mobility, survivability, lethality, and reliability necessary to ensure the success of a battle force will require that the Army focus now on ways of reducing the logistics support requirements of future combat systems.

Analyzing logistics trade-offs during the planning and implementation of systems will be critical. Of all advanced technologies considered in *STAR 21: Strategic Technologies for the Army of the Twenty-First Century,* computer simulation and visualization technology was recognized as the most relevant to the development of new Army systems. With improved modeling and simulation tools, the Army can identify, analyze, and evaluate alternatives and determine optimum system characteristics for reducing logistics demands at minimum expense. State-of-the-art modeling and simulation tools could also be used to test operational tactics and procedures, train soldiers, and verify doctrinal precepts.

Recommendation 7a. The Army should develop the necessary modeling and simulation tools for conducting logistics trade-off analyses at all levels of design, from small-scale components to fully integrated systems.

Recommendation 7b. To facilitate model development, logistical data from past military operations must be compiled and maintained in useful formats.

Recommendation 7c. Logistics trade-off analyses should be included in the Army's system acquisition and integrated logistics support processes.

1

Introduction

The movement and sustainment of military forces, otherwise known as logistics, are central to success on the battlefield. From the World War II "Arsenal of Democracy" to the strategic positioning of superior technology that guaranteed success in the Persian Gulf, the Army has always counted on practically unlimited logistical support. However, the need for the rapid deployment of power at any point on the globe, and post-Cold War reductions in strength are forcing the Army to change the way it will fight future battles.

These changes will require that the traditional logistics burdens—such as fuel, ammunition, food and water, spare parts, and electric power—be accommodated in new ways. Besides reducing demand, requirements for logistics infrastructure (personnel and equipment) to perform maintenance, transportation, medical, and other combat service support functions will also have to be minimized.

The Army envisions that by 2025 it should be capable of rapidly deploying a highly effective battle force practically anywhere in the world, and, if necessary, follow up the entry force with heavier, less strategically mobile forces. The rapid projection of an initial battle force will require that its logistics support requirements be substantially smaller than for present forces. Meeting the logistical needs of the Army in 2025, the so-called Army After Next (AAN), will require long-term investments in science and technology (S&T) that significantly reduce logistics demand.

Logistics considerations—weight, volume, transport modes and distances, frequency of resupply, etc.—are essential to the evaluation of prospective systems and research initiatives. The intelligent design of systems can improve logistics efficiency, and research dollars invested up front for the development of the design tools, materials, or software would be returned many times over if they reduce requirements for expensive items such as heavy lifters, spare parts, and fuel. Because much of the necessary research and development can be just as readily funded by the U.S. Department of Defense (DoD) or commercial sources, the Army should determine the research and technology development objectives that are most worthy of relatively scarce Army research dollars.

In September 1996, the National Research Council (NRC) Board on Army Science and Technology conducted a roundtable discussion of the AAN with members of the Army Training and Doctrine Command (TRADOC) and the Headquarters, Army Materiel Command (AMC), including key members of the Army Research Laboratory (ARL) and Army Research Office (ARO). The discussion was part of an early attempt to identify Army requirements for S&T in 2025, and it led to an extended process now under way to refine these requirements.

The planning and development for combat systems, such as the future combat system (FCS), future scout and cavalry system (FSCS), soldier as a system, and Army tactical missile system (ATACMS), among others, has already influenced long-term research objectives in competition for defense dollars. An assessment of technologies focused on possible reductions in logistics support for future systems would provide the Army with crucial information for deciding on future research and technology development.

Subsequent studies and workshops have concentrated on advantages in combat effectiveness. In these studies, mobility, survivability, and lethality were considered with little regard for logistical impact. Future technologies for the Army have been the subject of several NRC reports, *STAR 21:* Strategic Technologies for the Army of the Twenty-First Century (NRC, 1992, 1993a), Commercial Multimedia Technologies for Twenty-First Century Army Battlefields (NRC, 1995a), and Energy-Efficient Technologies for the Dismounted Soldier (NRC, 1997a). Technologies reviewed and recommended for research in these studies have all had a potential impact on logistics, but this is the first NRC study in which logistics is the principle criterion for evaluating and recommending research and technology development.

STATEMENT OF TASK

The Committee to Perform a Technology Assessment Focused on Logistics Support Requirements for Future Army Combat Systems, referred to as the Army After Next Logistics Committee, was formed in August 1997 to conduct a multidisciplinary study of long-term Army S&T investments that are likely to have the biggest impact on reducing logistics demand for the AAN. See Appendix A for the complete Statement of Task.

The Army requested that the NRC perform the following major tasks:

- Understand the importance of logistical considerations to successful battlefield operations and the likely impact of different enabling technologies on logistics support.
- Review concepts under consideration for soldier and battlefield systems for the AAN time frame.
- Analyze enabling technologies on which capabilities contemplated for the AAN will depend, and propose alternative technologies that would reduce the need for logistics support.
- Identify and evaluate areas of research that would reduce the logistics requirements for systems and operational concepts in the 2025 time frame of the AAN.
- Develop specific recommendations for the Army's S&T investment strategy, including research objectives and a road map for achieving them.

CONCEPT FOR ARMY AFTER NEXT OPERATIONS

In the last decade, the Army's modernization efforts have focused on achieving "information dominance" of the battlefield by making full use of information technologies. The evolving "digitized" force, known as Army XXI, will be realized in 2010. Beyond Army 2010, TRADOC has been charged by the Chief of Staff to investigate revolutionary capabilities achievable for an AAN in the year 2025. The AAN will depend on accelerated changes, even revolutions, in mobility, lethality, survivability, and sustainability that will dramatically increase the Army's capabilities to achieve full-spectrum dominance of the battlefield. Requirements for the systems that will be added to Army XXI to make up the AAN have not yet been determined.

In fact, at the time of this study, the AAN concept is becoming a cyclical process involving war games, analyses, and evaluations by the Army. This process was described to the committee as a concept exploration to define characteristics of a future Army capable of deploying a highly lethal battle force anywhere in the world on short notice.

With technological superiority, the AAN battle force would collapse an opponent's center of gravity before opposing forces have had time to "set," that is, to "dig in" following an act of aggression. The self-sustained battle force would be capable of delivering a devastating surgical blow in 14 days or less. Then, depending on the mission, the battle force would be followed by Army XXI forces.

The AAN tactical concepts and technologies are still notional but are considered possible in the 2025 time frame. Army 2010 is a major milepost on the road to the AAN along with operational concepts promulgated by the Joint Chiefs of Staff in *Joint Vision 2010* (DoD, 1996).

To ensure its success, the AAN must project forces with superior tactical and operational mobility, highly lethal and survivable weapons, and systems that exhibit new standards of reliability and sustainability. Key ingredients will be superior intelligence capabilities (information dominance) and operational airlift capability to transport armaments, vehicles, and soldiers fully prepared to engage in immediate battle over long distances.

The AAN concept proposes an Army made up of the AAN battle force (up to 20 percent) and Army XXI forces (80 percent). The rapidly deployable battle force will respond to contingencies from the continental United States within 48 hours, and, if necessary, be followed by the heavier Army XXI forces. The battle force would consist of units of up to 8,000 soldiers equipped with highly sophisticated weapons and vehicles capable of engaging and defeating a heavily armored enemy force. Compared to conventional operations, which averaged 40 km/h in the Gulf War, the battle force would move from a staging area and engage the enemy at speeds averaging 200 km/h (Scales, 1997).

The battle force would normally be part of a joint (multiservice) or combined (multinational) combat operation and would be capable of operating in densely populated urban areas when necessary. Operational emphasis will be on the vertical dimension for the inherent advantages of owning the "high ground." The vertical battle space will enable other forces to focus essential capabilities in general support (GS) of the AAN battle force, including ground and air platforms to deliver supporting fire, unmanned aerial vehicles (UAVs), and command, control, communications, and intelligence (C3I) for information dominance provided by low-, mid-, and high-orbit satellites. Figure 1-1 illustrates how the vertical battle space of the future compares to the linear battlefield of the past along with elements of the anticipated AAN operating environment.

This study focuses on logistics support requirements for systems used by the AAN battle force. These include highly mobile, lethal, and survivable combat vehicles and other weapons platforms. The battle force will also have sophisticated communications capabilities that will enable soldiers to maintain full situational awareness (SA), including near real-time damage assessment. The battle force will usually be augmented by supporting firepower and transport provided by the Air Force and Navy. All vehicles and equipment will necessarily be designed to require minimal logistics support because battle force units will have to be self-sustaining (i.e., require no support from logistics organizations external to the battle force) for up to 14 days.

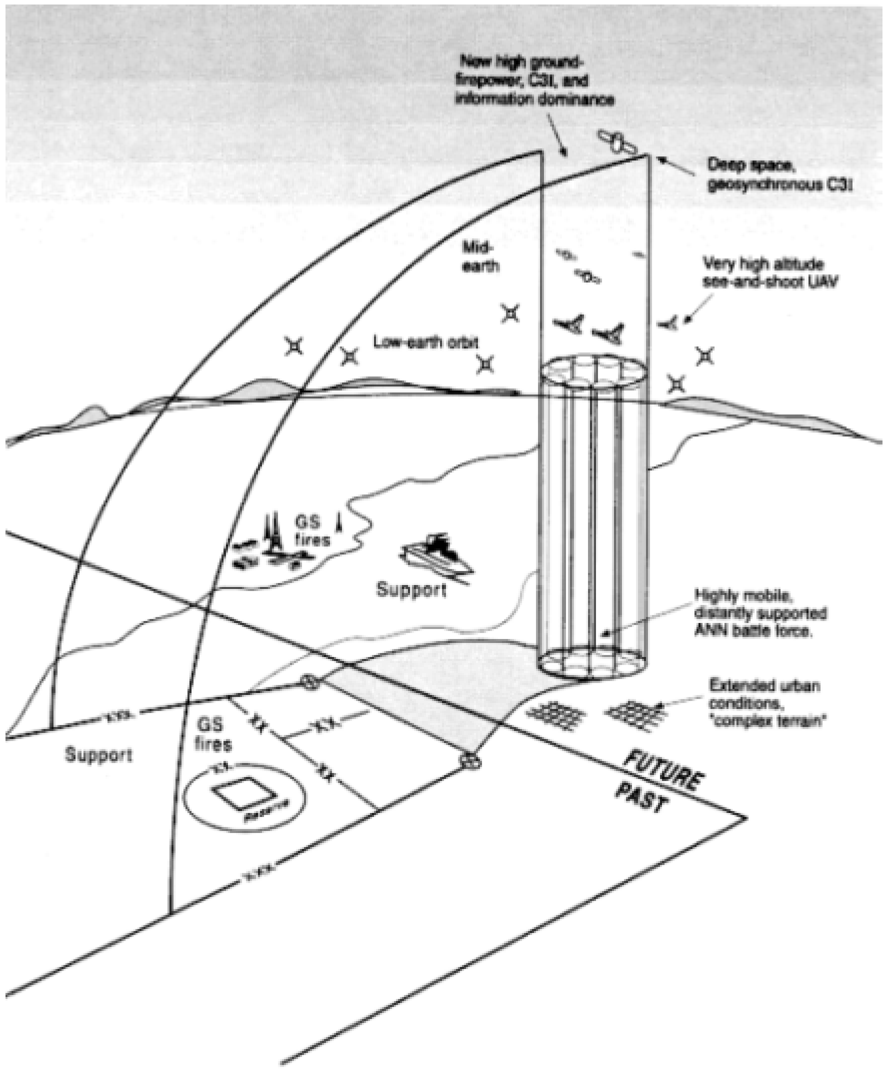

Figure 1-1
Illustration of the Army After Next operating environment. Source: Scales, 1997.

In establishing a baseline for applicable AAN technologies, the committee assumed that between now and 2025 Army doctrine and culture will evolve in parallel with technology and that the Army XXI forces will evolve from the fully-digitized units now being formed. The committee also assumed that planned improvements in logistics support capabilities would enable coherent logistics support of both the AAN battle force and the follow-on Army XXI forces.

STUDY CONCEPT

The starting point for this study was a series of briefings by TRADOC, which is leading the AAN initiative. Major General Robert Scales, past TRADOC Deputy Chief of Staff for Doctrine, provided the background and description of the AAN concept as it had matured since 1996 (Scales, 1997). TRADOC also provided a staff representative to assist the committee during the study.

The committee focused on logistics burdens and systems associated with the tip of the AAN spear, the AAN battle force. To determine a relationship between logistics and the AAN, the committee had to establish a baseline AAN concept and to understand the traditional military logistics burdens. Characteristics of the systems that would be needed to implement the AAN concept could then be used to find ways to reduce or eliminate the logistics burdens through the selection and development of appropriate technologies.

The committee was aided during the fact-finding phase of the study by representatives of Army and DoD organizations including the AMC, ARL, ARO, and various AMC research, development and engineering centers; the Army Logistics Integration Agency; the Army Combined Arms Support Command; the Army Corps of Engineers Waterways Experiment Station; the Army Science Board; the Air Force Office of Scientific Research; the Naval Research Laboratories; and the Defense Advanced Research Projects Agency (DARPA). See Appendix B for a complete list of the committee's fact-finding activities and briefers.

It is clear that the Army alone cannot provide for all of the desired AAN capabilities with a fixed number of research dollars. Therefore, AAN systems will depend heavily on S&T breakthroughs made by DoD and commercially sponsored research, possibly in response to the requirements of other government and commercial customers. In determining applicable AAN technologies, the committee interpreted "requirements for Army research" in the broadest sense, that is, without regard to who might eventually sponsor the research.

The committee assessed the likely impact of various technology developments on logistics demand and recommended that the most appropriate technologies be included in the Army-sponsored S&T program. The discussions and assessments of technologies were facilitated by the diverse expertise of committee members, but in some cases the discussions were limited because the committee did not have access to classified government requirements and research.

REPORT ORGANIZATION

This report documents the observations and findings, specific research and technology development objectives, and the general conclusions and recommendations of the study. It includes the committee's interpretation of Army requirements and assesses technologies that the committee judged to be both essential to the realization of the AAN vision and likely to reduce logistics demands.

The committee approached its task by grouping technology areas likely to affect AAN logistics into three broad (and overlapping) categories of operational requirements: mobility, engagement, and sustainment. During the fact-finding phase of the study, the committee was divided into three panels focusing on these three categories.

The broad functional categories of *mobility* and *engagement* remained useful throughout the study for analysis and discussion of logistics burden-reducing technologies. Technologies to reduce *fuel and energy* burdens and technologies to improve the *reliability* of combat systems emerged from the analysis of sustainment issues. A fifth technology category, *modeling and simulation* to support logistics trade-off analyses, emerged during the committee's investigation of mobility issues, and modeling and simulation (M&S) was seen to play an essential role in elevating logistical considerations to the same level as other performance factors in the design and acquisition of combat systems. Without the capabilities to model logistics demands of systems while they are still in the concept stage and to quantify the impact of technological and design alternatives on logistics demands, the Army will probably not reduce logistics demands or even hold logistics demands at present-day levels.

Chapter 1 (Introduction) provides the background, Statement of Task, and overall concept for the AAN, as well as the study concept and report organization. Chapter 2 (Logistics and the Army After Next Requirements) discusses the role of military logistics, the AAN logistics burdens, and mechanisms for reducing the burdens.

Chapters 3 through 7 assess the five functional technology categories described above. Chapter 3 (Logistics Trade-off Analysis) describes the key role of M&S technology. Chapter 4 (Fuel and Energy) discusses reducing the fuel burden by focusing on technologies that would reduce energy demands. Chapter 5 (Operational and Tactical Mobility) and Chapter 6 (Engagement) discuss technologies to support Army mobility and engagement system requirements. Chapter 7 (Reliability Concepts) describes the considerations for reliability needed to reduce the logistics support requirements of AAN battle force missions.

Chapter 8 (Soldier Sustainment) discusses the soldier as a combat system with special logistics requirements. Chapter 9 (Joint Force Requirements) describes requirements outside the Army's exclusive purview that bear on AAN requirements and on the determination of appropriate Army research and technology development. Chapter 10 (Investment Strategy for Research and Technology Development) provides a road map for reducing logistics demand for AAN systems by proposing specific objectives and recommending areas for research and technology development to achieve the objectives. Finally, Chapter 11 (General Conclusions and Recommendations) enumerates the general conclusions and recommendations of this study.

2

Military Logistics and the Army After Next Requirements

[T]he modern ground army has become shackled to its base, unable to venture far afield because it can not risk severance of its line of communications. Despite all its vehicles, the modern field army's mobility is actually extremely limited, for its knapsack is relatively small in terms of the days of supply it can carry.

Roland G. Ruppenthal
Logistical Support Of The Armies
Us Army in World War II, Vol. II

We have a clear vision for 21st century global military logistics. It is a system based on efficiently distributing resources, rather than stockpiling supplies, providing the right support, at the right time, in the right place - any place on earth.

General Dennis Reimer
Chief of Staff of the Army
1 February 1998

In the new style of war, superior logistics becomes the engine that allows American military forces to reach an enemy from all points of the globe and arrive ready to fight. . . logistics has always assumed a degree of importance far beyond that of merely sustaining the force in the field. . . the strength of the logistics engine determines the pace at which an intervening force makes itself secure. . . the length of a [military commander-in-chief's] CINC's operational reach will be determined largely by his logisticians.

MG Robert J. Scales
Commandant, U.S. Army War College

The annals of military history are filled with discussions of combat operations, but much less has been written about the support required to transport and sustain combat forces on the battlefield. Yet no commander can operate long without logistical support. Alexander, Hannibal, Napoleon, Bismarck, and Hitler all encountered the challenges of moving and sustaining military forces. The first three overcame the challenge, but the other two did not.

MILITARY LOGISTICS

Logistics is the process of planning and executing the movement and sustainment of operating forces in the execution of a military strategy and operations.
Joint Publication 4.0
Doctrine for Logistics Support of Joint Operations,
January 27, 1995 (DoD, 1995)

Military logistics systems provide the resources for mobilizing, deploying, sustaining, reconstituting, and withdrawing operational forces from combat or other military operations. Logistics systems include the materiel, services, and equipment, as well as the organizations needed to transport, supply, maintain, and care for operational forces. Because logistics forces do not normally engage the enemy and must be supported themselves, every effort is made to keep the ratio of logistics forces to combat forces ("tail-to-tooth" ratio) to a minimum. On the modern battlefield, the Army must not only support itself but, under cross-servicing agreements and executive agency responsibilities, must also provide certain types of supplies to the other services and, under some circumstances, to coalition partners. Some logistics functions are carried out for the Army by joint organizations and the DoD, as well as by the other services. The Defense Logistics Agency provides a variety of supplies, including fuels, directly to operational forces. Depending on the geographic area, naval and air forces provide construction, medical support, and other logistics services.

Strategic, Operational, and Tactical Logistics

Logistics activities in the past have been conducted on three levels: strategic, operational, and tactical. Technological advances in information systems and global transportation have blurred, if not eliminated, the distinction between these levels.

Strategic logistics activities are conducted at the national and international levels and include everything from defining requirements to the acquisition of materiel to the distribution of materiel to operational forces. Strategic logistics includes planning for and deploying personnel, equipment, and supplies to the theaters of operations and returning them to the United States.

Operational logistics take place within the theater of operations but are not directly related to combat operations. Operational logistics includes the reception, storage, and distribution of supplies and personnel. It also includes processing casualties, maintaining equipment, and providing and maintaining in-theater transportation systems.

Tactical logistics are conducted by units in combat, usually at the division level or lower. Some units engaged in direct combat have minimal logistics components, but most rely on separate logistics-oriented units to provide support. The purpose of tactical logistics is to enable combat units to conduct continuous military operations.

Historical Analysis of the Impact of Logistics on Modern Warfare

World War I was a low-mobility war. Trench warfare involved limited penetrations of the opponent's lines. Although logistics support was important in World War I, it did not have to cover great distances. Once mechanized armored vehicles were introduced, the logistics requirements for fuel, ammunition, and battlefield maintenance became apparent. U.S. combat forces deployed to Europe relied heavily on logistics support from the Allies because U.S. industries had been unable to gear up for the conflict. The distance between Europe and the U.S. and a limited sealift capability to transport supplies restricted support from home.

World War II was in many ways a contest of strategic logistics systems. When the United States declared war on the Axis powers, the country did not have the capability to field, deploy, or equip a substantial fighting force. Over a period of two years, "the Arsenal of Democracy" grew in size and gave the United States and its allies a war-fighting capability never before seen. By 1944, personnel, supplies, and equipment were flowing to both the Pacific and European theaters of operation. Even with the massive buildup before the Normandy invasion, however, the campaigns on the continent were soon restrained by the inability of the Allies to move adequate supplies from logistics bases in England to advancing armies. Patton's Third Army ran out of fuel and had to interrupt its thrust into Germany. (Earlier in the war, at the tactical level, General Rommel's efforts to defeat the British had been hampered by the lengthy supply lines and the logistics required to support the units moving supplies.)

In many respects, the Korean Conflict mirrored the experience of World War II. Because the war was not expected, the United States was unable to deploy adequate forces immediately to the battle area and required time to build up its strategic logistics system. After the Inchon invasion, the challenge became one of operational and tactical logistics as U.S. forces raced north to the Yalu River.

The U.S. involvement in Vietnam changed over time from an advisory role with limited logistics requirements to a full-scale commitment of combat units in conventional warfare. However, prior to the initial movement of forces to the theater and throughout the buildup phase, U.S. logistics forces had been developing an infrastructure in Vietnam to support offloading and handling supplies and equipment. Even though new ports were constructed at several locations, the deployment of forces was constrained by the overall paucity of facilities. In Vietnam, logistics support at the tactical level was made easier by the new-found capability to use fixed-wing and rotary-wing aircraft to move supplies from base camps to forces in the field.

When the Persian Gulf War began, the United States was fortunate that Saudi Arabia possessed a significant port and airfield infrastructure (developed over the preceding 20 years by the U.S. Army Corps of Engineers for the Saudis), but the bases were not equipped to support extended military operations. Although troops could be moved to the theater quickly by air, the strategic transport of their equipment by sea was slow. Even after the troops were reunited with their equipment, General Schwarzkopf, contrary to the advice of his staff, insisted on having a 60-day supply of provisions on hand before initiating any operations (Scales, 1993). The logistics requirements were enormous. The Saudis provided U.S. forces with 21 million gallons of fuel each day, and more than 350,000 tons of ammunition were transported from the United States to the theater. Medical personnel constituted 5 percent of the total force. A combined contractor and military transportation organization worked around the clock to move supplies and equipment from the ports to positions near the battle areas.

Partly because the war was over so quickly, but also because of overstated requirements and poor information flow, large amounts of supplies were returned from the theater untouched. About 25,000 containers with unidentified contents were returned. More than 300,000 rounds of artillery, tank, and aircraft ammunition were returned, in large part because outdated consumption rate estimates were used. In World War II, an average of 14 rounds were required to kill an enemy tank in tank-on-tank engagements. With the advent of the Abrams tank, the average in the Persian Gulf War dropped to 1.2 rounds per kill. Between aircraft and ground ammunition, the United States had 40 rounds available to kill each Iraqi tank (DoD, 1994).

Military interventions and operations in Bosnia, Rwanda, and post-Gulf War Kuwait have been characterized by ad hoc organizations, buildups, and the use of stocks of materiel prepositioned in depots at forward locations or ships in the United States or at sea. Nevertheless, the United States was unable to move equipment rapidly to the mission areas. In the case of Rwanda, the ability to respond was severely hampered by the total lack of infrastructure in the mission area and by the distance between Rwanda and previously used U.S. and allied forward staging areas. Fortunately, the tactical logistics problems were solvable because of the short duration of these operations.

CONCEPTS OF WARFARE FOR THE TWENTY-FIRST CENTURY

The military community agrees that warfare in the twenty-first century will be considerably different from warfare in the twentieth century. In *Joint Vision 2010,* the Chairman of the Joint Chiefs of Staff (JCS), the senior military officer in the defense structure, has defined a vision of warfare in the first decades of the twenty-first century (see Figure 2-1). This planning document describes a military that will have total SA of the battle space in which it will operate; the ability to protect its forces from enemy attack on the ground, from the air, or from space; and the ability to provide focused logistics support (DoD, 1996).

According to the JCS, focused logistics represents ". . . the fusion of logistics, information, and transportation technologies for rapid crisis response; deployment and sustainment; the ability to track and shift units, equipment and supplies even while enroute, and delivery of tailored logistics packages and sustainment directly to the war-fighter" (DoD, 1997a).

Focused logistics will provide forces in the battlefield area with command-and-control systems that closely link operations with logistics, enabling logisticians to provide combat commanders with whatever they need, whenever and wherever they need it. Focused logistics will be truly "joint" logistics: wherever feasible, logistics functions of the services will be combined or one of the services will be assigned as the lead agent for a function or supply item. U.S. forces will also rely more on support from host nations and allies. Information will give the logistician "total asset visibility," the ability to determine seamlessly what equipment and supplies are available in the operational theater or in the United States and where they are. During the Persian Gulf War, the U.S. military operated with 26 separate logistics data systems that had few interconnections (Fontaine, 1997). The logistics force of the future is expected to operate with an "agile infrastructure" that will permit combat forces to take with them only what they are sure to need—right-sized, "just-enough" inventories—and enable logisticians to supplement this support whenever and wherever necessary.

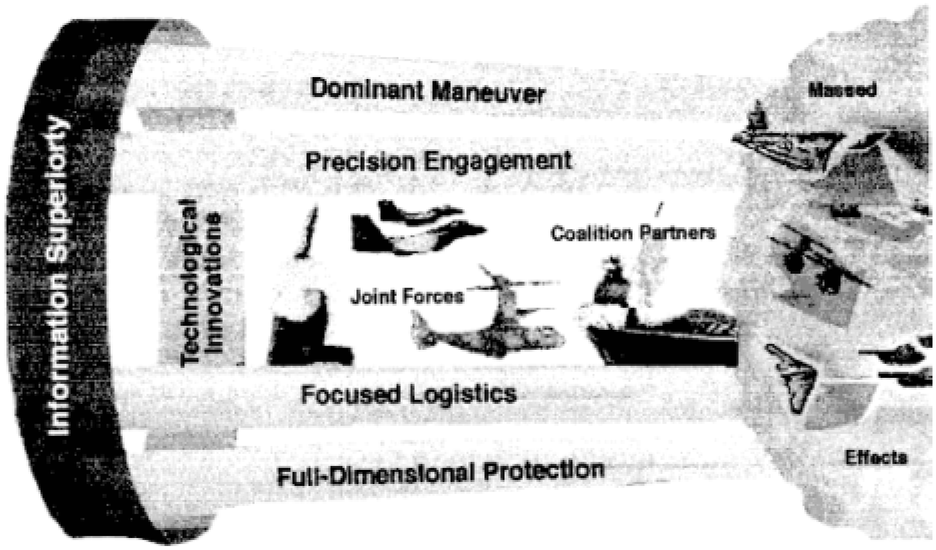

Figure 2-1
Joint Vision 2010 operational concepts. Source: DoD, 1996.

Building on the concept of focused logistics, the Army has postulated a revolution in military logistics (RML) to leverage advances in information systems technology and fuse operational concepts with logistics systems. The RML will involve a shift towards distribution-based systems (rather than the accumulation of supplies), real-time situational understanding, new organizational designs, and proven commercial business practices. The goal of the RML is to reduce sustainment requirements and logistics infrastructure by focusing on a high velocity, agile, responsive logistics system based in the continental United States (DA, 1997). In developing the logistics structure for Army XXI, logistics planners are incorporating the RML concepts into force structures and reducing the need for forward logistics units.

Logistics Concepts for the Army After Next

Although few specifics have been defined for the AAN, the committee was able to derive logistics support requirements for an ideal AAN battle force from the operational concept described in Army briefings. The characteristics of the ideal battle force are listed below:

- The AAN force will be deployed to a staging area near the operational area via strategic air and sea transport provided by the other services.
- The battle force will establish a logistics support base (battle unit support element) at the forward staging area.
- The battle force will use Army resources to move to the battle area.
- The average speed of movements from the staging area to contact with the enemy on the battlefield will be 200 km/h.

- The battle force will carry adequate supplies, including fuel and ammunition, to sustain itself for 14 days, a two-week combat pulse.
- The battle force will only depend on support from external logistics organizations between combat pulses.
- Once its mission has been accomplished, the battle force will be rapidly withdrawn.

Logistics Burdens for the Battle Force

Combat commanders have long understood that their operational flexibility is limited by logistics and that plans for combat operations must be matched to the availability of logistics support. Any materiel[1] or organization that does not contribute directly to combat effectiveness is considered a logistics burden. This study focuses on reducing logistics demand by reducing logistics burdens.

The principal logistics burdens are the fuel, ammunition, food, water, and spare parts necessary to sustain the force during operations. But the logistics burdens also include logistics personnel and equipment in combat support and combat service support organizations (providing supplies, maintenance, transportation, medical services, and other support for the combat units) and the supplies and support required to keep these logistics organizations in operation. Reductions in the logistics demand for fuel, ammunition, water, food, and spare parts consumed during an operation can lead to even greater reductions in logistics burdens. Therefore, one significant way to reduce the logistics burden of a battle force is to reduce the number of logistics units (both personnel and equipment).

Because of the considerable uncertainties about the logistics requirements of combat forces and whether this support will in fact be available when needed, the military has always planned to have "more than enough, just in case." As a result, large stores of supplies and large numbers of specialized logistics troops are usually transported to the combat zone and moved along behind the fighting forces.

A light infantry division of 11,520 troops, for example, is deployed with a weight of 18,122 tons.[2] This includes the weight of the soldiers, their personal gear, and all equipment. It also includes one day of ammunition; five days of rations, construction materials, and personal items; and 15 days of clothing, petroleum products, medical supplies, and spare parts. Although the deployment weight includes combat and support units in the division organization, it does not include the weight of the combat and support units external to the division that are needed to support the division. This so-called "light division" deploys with 3,841 vehicles and 83 aircraft. To move this force requires 816 C-141 sorties or 61 C-17 sorties. A "heavy" armor division, by contrast, weighs out at 102,052 tons for 17,186 troops and 8,125 vehicles (1,249 of which are tracked vehicles). It therefore generates a considerably larger transportation requirement than the light division (DoD, 1997b).

These estimates are based on a table of organization and equipment (TOE) for an existing Army organization. Although the Army has not yet developed a TOE for an AAN battle force, the Army's experience with planning for the deployment and

[1] "Materiel" refers to equipment, apparatus, or supplies for a military force.
[2] Unless otherwise indicated, tonnage is measured in short tons.

sustainment of existing units can be used as a basis for estimating the logistics burdens of an AAN battle force.

Army estimates for the number of troops in the AAN battle force units varied over the course of the study. The initial estimate of the force was 8,000 soldiers. The Summer 1998 AAN War game assumed a mechanized air assault unit of 5,284 soldiers and 1,998 vehicles (air and ground).

If one assumes a hypothetical AAN battle force of 8,000 soldiers and estimates the deployment weight to be on the same order as a current light infantry division, the deployment weight for the AAN battle force would be 12,585 tons. An increase in the ratio of vehicles to soldiers would add to this. Assuming there was no replenishment for the first combat pulse, the deployment weight would be increased by the additional supplies needed to bring all categories of supply up to a 14-day level.

BURDEN REDUCTION GOALS

After reviewing logistics burdens in past military operations and Army concepts and plans for the future, the committee determined that the logistics burdens, especially fuel and ammunition, could be readily translated into logistics burden reduction goals to reduce logistics demand. The committee concentrated on the following logistics burden reduction goals:

- reducing fuel demand
- increasing fuel energy by weight
- managing fuel and energy
- reducing lethal system weight
- reducing the number of rounds of ammunition required per target
- reducing weight per round of ammunition
- increasing system reliability
- lightening soldier systems
- increasing soldier effectiveness
- optimizing system designs
- providing "just right" logistics

In the initial Army briefing to the committee in September 1997, the AAN concept was based on a self-deployment capability for AAN vehicles. Both the Army and the committee later concluded, however, that vehicles would have to be airlifted to the mission site from a forward base and would require near-vertical insertion and extraction (or very short landing and takeoff). This airlift requirement is an additional logistics support requirement for transporting the force to and from the battle area. Considering how few airlift alternatives are available, the committee concluded that the Army would have to consider airlift capabilities as part of the battle force requirement.

The operational requirement for highly mobile vehicles that can be easily and rapidly transported to the mission area in large numbers prompted the committee (and Army planners and developers) to focus on relatively lightweight combat vehicles (15 tons or less). Once inserted by air, these combat vehicles must be prepared to accomplish any or all of a variety of combat missions, operating for up to 14 days without logistics support from outside the battle area.

Because these vehicles must operate under very tight constraints, every function and every capability must be considered against every other function and capability. For instance, given a fixed weight limit far lower than the weight of existing armored vehicles, increasing protective capability may require a reduction in weapons system capability. Increasing the capability of a vehicle to negotiate obstacles may increase weight and reduce fuel-carrying capacity. Thus, trade-off analyses will be required at all levels—among systems, among components, and among competing technologies and materials.

The committee considered technologies for the AAN battle force in the context of functional requirements for mobility, engagement, and sustainment systems. The committee then evaluated technology application areas[3] for systems needed in each category to determine technologies most likely to affect AAN logistics demands.

It should be noted that the committee did not have access to classified material and information on relevant development programs, in particular, armor, C4ISR (command, control, communications, computers, intelligence, surveillance, and reconnaissance), and signature reduction, was not available to the committee. In addition, the committee was told that the Army expects to complete development of its C4ISR structure by 2010 and that the committee should assume that the planned structure would be adequate to support future Army systems. Because of the critical relation between C4ISR and logistics demand, the committee rejected this assumption and provided recommendations on several C4ISR issues based on the expertise of committee members. Thus, given background information on logistics and the AAN, the committee investigated technology developments necessary to reduce logistics burdens while meeting AAN performance goals.

[3] These included: armor; lightweight materials; command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR); global positioning; energy storage, management, and conversion; hydrogen storage; lightweight nuclear power; modeling and simulation; ordnance (gun systems, small rockets, lasers, energetics); reliability (prognostics, on-site repair and manufacturing, physics of failure); robotics; sensors and guidance; signature reduction; soldier sustainment; and tactical mobility systems.

3

Logistics Trade-off Analysis

The Army depends on a broad array of analytical techniques to assist in decision making. For several reasons, these techniques will play an even larger role in designing the AAN. First, systems for the AAN will be developed and fielded in an environment of increasing resource constraints, and trade-offs, particularly trade-offs that result in logistical savings, will become increasingly important. Second, an AAN battle force that can meet operational performance objectives and be self-sustaining for up to 14 days will require revolutionary advances in mobility and reliability. The conflicting technical requirements associated with these objectives will require many trade-offs in materiel capability and force structure. Making these trade-offs in a reasoned way will require focused *trade-off analysis.* In this chapter, the committee argues that AAN trade-off analysis must be supported by Army-developed modeling and simulation (M&S) tools.

FACTORS IN TRADE-OFF ANALYSES

To assess the potential impact of various technologies on logistics burdens, the committee was divided into three panels that focused on mobility, engagement, and sustainment functions. The panels quickly found that many of the technologies and system concepts being considered for the AAN battle force would have pervasive effects on both AAN operational capabilities and logistics burdens. However, the effects of one technology or system concept often conflicted with the effects of another. The panels found that all of them had both advantages and disadvantages. In short, there were many potential solutions but no simple or easy answers to meeting the needs of the AAN.

At first glance, the target date of 2025 for an AAN operational capability appears to be far away. But existing system concepts, such as the FCS (future combat system), the FSCS (future scout and cavalry system), and the Army tactical missile system, do not address AAN battle force requirements directly. The new AAN systems will have to be built in prototype, tested, refined, manufactured, and distributed to troops for a substantial period of time before they can be integrated into the force. These steps to *fielding* a mission-ready AAN battle force will require at least 15 years *after the major design has been completed.* A fully engineered design, ready for prototyping and subsequent engineering and manufacturing development must, therefore, be completed by 2010. Thus, critical decisions on the materiel and technologies in the system designs will have to be made *in the next decade.*

Making the difficult trade-offs to arrive at optimal designs for all AAN objectives, including reducing logistics burdens, will be time-critical. Given the complexity of the decisions, the range of possibilities, and the tight constraints on resources and schedules, analytical approaches fully supported by M&S tools offer the best chance of meeting the target date without sacrificing AAN program goals in general and the goal of reducing logistics burdens in particular.

Capabilities for AAN Performance and Reducing Logistics Burdens

Box 3-1 is a list of representative performance capabilities that have significant logistics consequences and are also dependent on choices of technology and design concepts. These capabilities must be addressed in the trade-off analyses that support system design decisions.

Many of these capabilities represent performance and logistics characteristics that are in direct conflict with each other and will require in-depth, quantitative analyses to make appropriate trade-offs. For example, if the objectives of high-speed cross-country mobility, improved fuel economy, and AAN mission reliability were pursued independently, the resulting design would have serious flaws. Achieving high-speed cross-country mobility may be at cross purposes with fuel economy and 14-day sustainment goals. Conversely, improving durability and mission reliability with heavy structural designs could decrease high-speed mobility and increase fuel consumption (the major logistics burden for the AAN battle force). Using M&S to analyze design options for all capabilities interactively and selecting the options with the best overall capabilities for AAN operations is the only affordable approach to deciding on trade-offs in time to proceed with development by 2010.

Almost all concept and technology trade-offs will have significant consequences for the self-sustainment goal of 14-days. To meet this goal, logistics must be a *primary objective, if not the highest priority objective,* for trade-offs in design and technology options. This will require reversing the conventional approach of first designing and fielding materiel and then turning to the logisticians to determine how to support it (Box 3-2). Materiel for the AAN will have to be *designed* to meet sustainment requirements as well as other performance requirements and affordability constraints (including life-cycle cost, not just acquisition cost).

BOX 3-1 Technology-Dependent AAN Capabilities with Significant Effects on Logistics Demands

Mobility

- High cross-country speed
- Low vehicle weight
- Fuel economy
- Engine duty cycle

Engagement

- Situational awareness
- Communications
- Precision-guided firepower
- Protection from projectiles and directed-energy weapons
- Stealth

Sustainment

- Mission reliability
- Fuel and ammunition resupply
- Energy management
- Subsystem durability

Trade-off analyses, using M&S tools to capture the complex interactions among design options and to quantify their relative values in meeting AAN performance goals, will be critical for reversing the conventional process. But reducing logistics burdens can only become a primary factor in trade-off analyses if the M&S tools can simulate all of the logistics-relevant aspects of the operational context for the system being designed. Unfortunately, many of the revolutionary new concepts and technologies being considered for AAN are beyond the capability of current M&S tools in two essential respects. First, because AAN materiel and operational concepts are *outside the box* of conventional materiel and force structures, they are also *outside the box* of existing M&S tools, which were designed for conventional systems and forces. Second, because logistics considerations have never before been a primary factor in design analysis, or even in engineering development and testing, current M&S tools do not necessarily model the elements of system operation that determine logistics demands.

BOX 3-2 14-Day Self-Sustainment Requirement Must Dictate Materiel Design

Traditional Model

- Design-driven logistics
- Accept existing system reliability standard
- "Just in case logistics" (take everything you might need)

AAN Model

- Logistics-driven design
- Design systems for AAN reliability standard
- "Just enough logistics" (take only what you need)

The extraordinary requirements for high-speed cross-country mobility, drastically reduced fuel consumption, and 14-day self-sustainment will challenge the Army to use advanced technologies in areas of system performance that have not been emphasized in the past. Enormously complex trade-offs in performance, logistics support, affordability (including life-cycle-costs), and schedules of AAN development are well beyond the capabilities of current analysis tools. In other words, existing M&S tools cannot support rational and timely trade-off decisions for AAN planners and materiel developers. If AAN planners want to field "out of the box" systems by 2025, they must support—and even demand—that M&S tools and technologies required for the analysis and design of AAN systems be developed in the next decade.

Requirements for AAN Trade-off Analysis

The committee identified three areas in which analysis capabilities, particularly M&S capabilities, will be critical to AAN trade-offs and optimization for reducing logistics demand: high-speed cross-country mobility; materiel reliability; and small unit and force-on-force engagement. Box 3-3 lists the M&S capabilities required in each critical area.

M&S for high-speed cross-country mobility must include reducing vehicle system weight and fuel consumption. Accurate M&S of (1) high-speed mobility across soft soils and moderate to rugged terrain, (2) loads that influence mission capability, and (3) fuel consumption and the life-cycle system cost for radical new vehicle designs will require significant advances. Simulation tools and capabilities will have to be greatly improved for mission rehearsal, for determining the logistics requirements of specific tactical operations (including operations with logistical constraints, such as fuel shortages, etc.), and for training drivers and operators (particularly for cross-country mobility).

BOX 3-3 Critical M&S Needs for AAN Trade-off Analyses in Support of Reducing Logistics Demand

High-Speed Cross-Country Mobility

- Vehicle system/subsystem trade-offs
- Mission rehearsal for logistics requirements
- Driver training to achieve mobility objectives

Materiel Reliability

- Mechanisms of failure modeling
- Uncertainty modeling
- Human factors modeling

Small Unit and Force-on-Force Engagement

- Integration with engineering models
- Sort out trade-offs

The committee identified materiel reliability as a critical capability for meeting the AAN operational objective of 14-day self-sustainment. Significant improvements in M&S capabilities, including additions to existing models and the implementation of new models, will be required to design systems and make the inevitable system trade-offs. A critical M&S capability will be the incorporation of reliability engineering into subsystem and component M&S to model mechanisms of failure.[1] Equally important will be improved representations of variable environmental conditions and human factors, two uncertainties in real-world performance that should be simulated as realistically as possible during design analysis.

The importance of linking engineering analysis tools to small-unit and force-on-force engagement models became clear as the committee discussed alternative system concepts and technology options with representatives of the Army's materiel development and war-fighting communities. Revolutionary tactical concepts being considered by AAN planners will have stringent performance and support requirements, which planners are assuming can be met by new systems based on advanced technologies. At the same time, novel and emerging technologies suggest all kinds of possibilities for new tactics and doctrines. These "requirement pulls" and "technology pushes" have created an overwhelming number of operational, technological, and materiel design alternatives the Army will have to evaluate in terms of performance, affordability, and logistics.

But trade-offs can only be studied effectively if the engagement models and the engineering analysis tools are linked. Requirement pulls must lead to specific, quantifiable performance constraints and objectives at all levels, down to the models used for engineering design studies. Promising technology-push opportunities must be weighed against each other and competing performance requirements using reliable, realistic parameters of system performance and limitations in force-on-force engagement models. The engagement models must constrain tactics and outcomes to parameters

[1] *Mechanisms of failure,* as used in this report, are causal links between physical properties at one level and performance characteristics at the next higher level of system structure or integration. The designer's knowledge of mechanisms of failure may come from statistical analysis of past performance of a material or structure in similar applications (often called statistics of failure), from a theoretical understanding of how certain properties relate to performance, or from engineering experience with the material or structure. Mechanisms of failure at the microscale in materials are commonly referred to as the *physics of failure* for that material in the application of interest. See Chapter 7 for a further discussion of mechanisms of failure as related to designing AAN systems for reliability.

based on solid engineering constructs rather than on wishful thinking. The committee found little evidence that M&S environments for engagement and engineering analyses are being linked. Nor has the Army made a concerted effort to implement linkages in the time frame relevant to AAN design decisions. This problem is analogous to the difficulties faced by manufacturers in effectively linking computer-aided design tools with manufacturing tools, an area that is receiving a great deal of attention in the commercial manufacturing sector.

Comparison with the STAR 21 Study

As a "reality check" on its finding that M&S capabilities will be critical to system trade-off analyses, the committee reviewed the results of an earlier, much larger study of future Army technologies. For that study, the NRC committee wrote a series of reports called *STAR 21: Strategic Technologies for the Army of the Twenty-First Century*. The *STAR 21* committee considered a broad spectrum of Army needs, although not the specific needs of an AAN battle force with the operational characteristics described in Chapter 2. However, the air-transportable "middle tier" force that was central to the *STAR 21* recommendations on force structure and strategy is roughly analogous to an AAN battle force (NRC, 1992, 1993a). In fact, most of the technology opportunities and AAN systems concepts now being discussed by the Army for the AAN were addressed in one form or another in the *STAR 21* reports.

Table 3-1 lists 14 high-priority technologies that were discussed in the *STAR 21* Long-Term Forecast (a 30-year technology forecast from 1990, the date of the study,

TABLE 3-1 Rank Ordering[a] of Technologies Identified in the STAR 21 Technology Relevance Matrix

Advanced Technology	Importance to Army Systems
Computer simulation/visualization	64
Complex systems design	61
Materials design by computation	52
Hybrid materials	51
Information explosion	49
Human-machine interfaces	33
Battlefield robotics	28
Battle zone electric power	28
Terrain-related technologies	28
Weather modeling and forecasting	21
Metals	14
Surface mobility propulsion	13
Ceramics	12

[a] Numerical values are the sum of (1) 3 times the number of systems for which this technology is critical, (2) 2 times the number of systems for which this technology is important, and (3) the number of systems for which the technology is relevant. Source: NRC, 1993a.

to 2020) and were included in the summary table of advanced technologies for 32 representative systems concepts. The rankings, which are based on ratings by the *STAR 21* committee, indicate whether advances in a technology area are required, important, relevant, or irrelevant to a class of systems. The *STAR 21* ranking shows that computer simulation is the highest priority technology for the analysis and design of complex systems.

Despite this strong endorsement more than six years ago of M&S technology for designing complex systems, the committee found little evidence that creating and implementing the M&S capability that is needed now for AAN analyses and designs has been given a high priority. The remainder of this chapter spells out in general terms the kind of M&S environment that will be necessary for analyses of AAN systems. Examples of M&S tools and needs are provided primarily to illustrate the general approach. Readers will find suggestions for specific M&S applications and unmet needs in Chapters 4 through 7 and Appendices C through F.

MODELING AND SIMULATION ENVIRONMENT TO SUPPORT LOGISTICS TRADE-OFF ANALYSIS

Figure 3-1 illustrates the linkage of M&S tools at multiple structural and functional levels using vehicle system design as a focus. (The same hierarchical concept

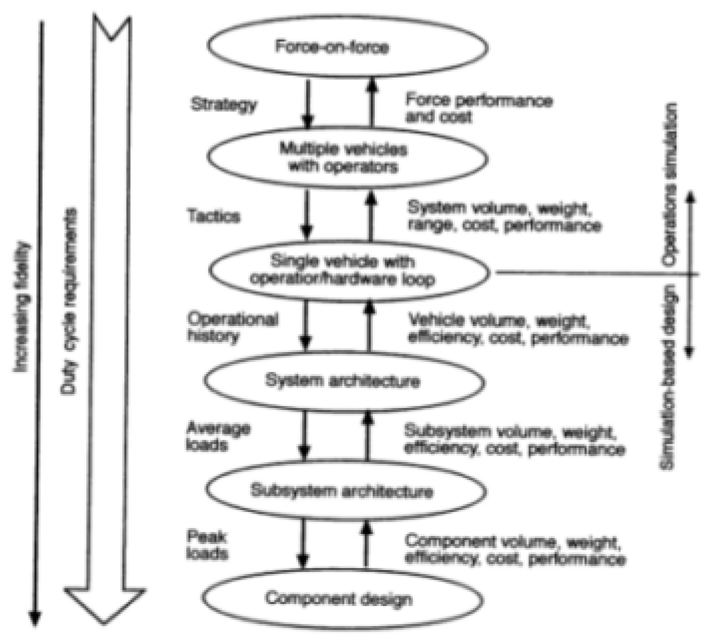

Figure 3-1
Hierarchical system of modeling and simulation for AAN trade-off analyses for a vehicle system.

applies to non-AAN systems and systems for different battlefield functions, such as lethal systems, energy systems, and communications systems, as well as mobility platforms.) Figure 3-1 is adapted from an in-depth virtual prototyping plan for hybrid electric vehicles (IDA, 1996a). Force-on-force simulations at the highest operational level of the drawing involve strategic and force-level performance and affordability issues. At the other extreme, tools for engineering analysis and design use peak load information from higher level simulations to drive detailed component designs toward meeting or undershooting constraints on volume, weight, and cost, while achieving or exceeding performance objectives.

Just as the force-on-force analysis at the top of Figure 3-1 involves a complex military system, the component analysis and design at the bottom of the figure involves complex engineering considerations. Figure 3-2 shows a few of the considerations involved in component design. Each design consideration requires information on duty cycle requirements from the next higher level analyses in Figure 3-1 to optimize rational designs, which in turn provide performance information for higher level analyses.

The Army has excellent computing facilities that can support the recommended spectrum of M&S tools. Many of the simulations require only workstations, which are available to virtually every scientist and engineer in the Army. In addition, the Army has invested heavily in shared-use supercomputers, which are readily available via high-speed networks. These prior investments in computing assets, as well as the availability of most software required to support the recommended hierarchy of M&S tools, will significantly enhance the cost-effectiveness of the recommended approach.

One might consider the M&S tools and the underlying enabling technologies depicted in Figures 3-1 and 3-2 as a "system of modeling and simulation systems." In keeping with the DoD high-level architecture (HLA) for M&S systems now being developed, a more accurate description would be a "federation of models and simulations," that is, a distributed set of models that can be either loosely or tightly coupled when used

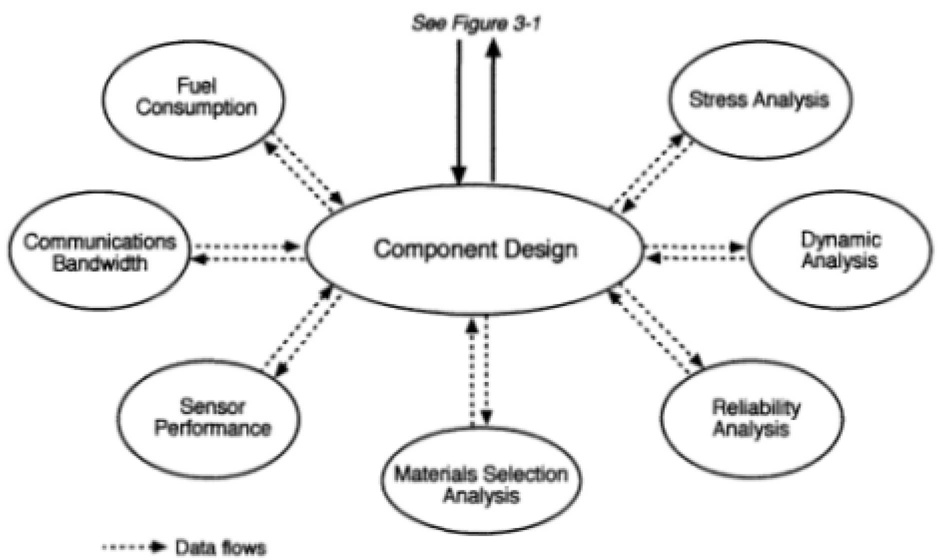

Figure 3-2
Component design considerations.

to support trade-off analyses, depending on the needs of the engineering and war-fighting communities. The concept and practice of using analysis tools like these have been well established in the commercial sector by Boeing, Ford, Chrysler, and other industry leaders. In fact, almost all competitive manufacturers of complex, technology-dependent products use this approach for developing new products to meet customer needs and stay ahead of competitors.

To illustrate the use of the M&S hierarchy shown in Figures 3-1 and 3-2, consider the conflicting AAN objectives of vehicles with high cross-country speed, high mission reliability, and low fuel consumption. A traditional approach to achieving high reliability, despite the extreme loads encountered in high-speed cross-country mobility, would be to incorporate more material into the vehicle structure, which would make the vehicle heavier and would increase fuel consumption. To overcome the fundamental conflicting trade-offs inherent in conventional technology, advanced technology concepts, such as active suspension and traction control, could be simulated in a virtual proving ground with a soldier driving the vehicle (the midlevel simulation in Figure 3-1). This simulation exercise could determine the loads on vehicle subsystems and the duty cycles required for the power train. Once these are determined, detailed subsystem and component designs can be carried out (the engineering simulations at the lower levels in Figure 3-1) to minimize weight and fuel consumption, subject to AAN mission constraints, especially reliability. Once technically feasible designs have been created, they can be simulated in an operational environment (the higher level simulations in Figure 3-1) to assess their performance against AAN mission requirements. If performance levels are inadequate, either another round of subsystem and component-level designs can be initiated to address the specific inadequacies or trade-offs can be identified and made. In practice, a combination of these two approaches—iterating the analysis cycle and making performance trade-offs—is usually used.

Using the M&S Hierarchy for Exploratory Development and Defining Research Needs

The distributed M&S environment described above is directly applicable to exploratory development at all of the levels shown in Figure 3-1. Exploratory development and engineering development involve using any of the constituent models for design studies, for modeling test scenarios for testing prototypes, or for testing proposed design changes prior to production. Exploratory development also involves different levels for system design analyses and trade-off decisions.

The committee believes that linking existing M&S tools to improve existing models or developing new ones to complete a distributed hierarchy for a broad application area (such as combat vehicle or projectile weapon systems), will involve more exploratory and engineering development than research. These linkages can be implemented using established, proven approaches that have been developed by the commercial manufacturing sector.

Although distributed M&S environments consistent with Figure 3-1 could be used for AAN design studies in broad application areas and are well within the Army's budget for technology development, the use of these environments will have serious implications for defining new research and technology development needs. In general, engineering design studies and system trade-off analyses for designing the first generation of AAN systems in the near-term will rely on current knowledge in the component-design considerations shown in Figure 3-2, which defines the *existing* technological options. If existing options have been exhausted and the performance goals defined at the higher levels in the hierarchy have still not been met, the systems designer will probably have to make performance trade-offs to complete a design for further development by 2010.

The models used for logistics trade-off analyses must be accurate. Simulations can only include what their creators build into them; they cannot generate basic new knowledge. Credible simulations can organize and present the trade-off information the Army will need to make rational decisions about AAN systems.

In the longer term, the absence of technology options that can meet the combined criteria for AAN operational goals will help to determine the direction of applied research. If applied research cannot meet these well defined needs, either because of a lack of fundamental knowledge or a lack of basic tools for solving the problem, the resulting *knowledge gap* can then be used to guide basic research.

The committee believes it would be imprudent for the Army to *rely* on either applied research or basic research to produce a proven new technology option by 2010 to solve a presently unsolvable system design problem. Nevertheless, some *research breakthroughs* could be proven in time to provide a new design approach or (more likely) to improve on one already formulated with existing technology options. Once a significant research breakthrough has been made, M&S can provide the engineering basis for incorporating it into design alternatives.

Near-term breakthroughs aside, the systematic approach to defining research needs based on hierarchically linked M&S environments will be vital to ensuring the *long-term technological dominance* (beyond 2025) of both AAN-style Army forces and the Army as a whole. The likely continuation of budgetary constraints and the importance of leveraging joint research programs and other DoD-level research to meet long-term Army needs are strong incentives for the Army to use this systematic approach. Appendix C includes an example of how the hierarchy shown in Figure 3-1 can be extended to a particular technological discipline (materials selection and design) to enable basic research.

To return to the central problem of developing a capability for near-term trade-off analyses that will achieve logistics reduction goals, the remainder of this section will use three kinds of design problems to illustrate the general concept of hierarchically linked, distributed M&S systems. The examples are drawn from the three focal areas listed in Box 3-3: mobility trade-off analyses for AAN combat vehicle concepts, trade-off analyses at the level of small-unit and force-on-force engagements, and AAN mission reliability trade-offs for AAN vehicle design.

Mobility Trade-off Analyses

Three mobility analysis capabilities start out as high-priority requirements for making AAN logistics trade-offs: comparative analysis of vehicle performance and logistics requirements; mission rehearsal to determine logistics requirements; and driver training for optimum mobility.

The strenuous vehicle system performance requirements implied by the AAN tactical concept, combined with the wide array of system and technology alternatives, dictates that trade-offs in vehicle performance objectives should be made early to achieve the goal of a 14-day mission without logistics support. Only high-fidelity simulations of vehicle operations in the anticipated operating conditions, including realistic modeling of the logistics requirements for those operations, can support the design decisions. Once a system that can model vehicle performance and relevant logistics has been implemented, that capability can be linked with other tools to support simulation of mission rehearsal for determining logistics requirements and for designing training simulators for drivers.

Modeling Vehicle Performance, Including Fuel Consumption

A starting point for M&S of the required vehicle performance is the North Atlantic Treaty Organization (NATO) Reference Mobility Model (NRMM), which was developed in the late 1960s and 1970s and has been validated and used constructively for the past two decades. The NRMM characterizes a vehicle's mobility in terms of speed and tractability. When values for these parameters are assigned, either from empirical knowledge or arbitrarily for a "what if" analysis, and a terrain database characterizing the field of operation has been chosen, the NRMM can predict the time required for a vehicle to move between two specified positions in a tactical environment.

However, the values for the speed, tractability, and fuel consumption parameters for NRMM are problematic at best for the advanced vehicle system and subsystem concepts being considered for the AAN. Engineering models can not yet accurately predict speed and tractability for vehicles with active suspension, all-wheel traction control, electric drive or a power source other than an internal combustion engine, and a host of related advanced technologies. Some combination of these technologies will undoubtedly be required to approach the AAN off-road mobility requirements. For example, current tractional force models that represent fundamental physical interactions (known as "first principles" models) between the traction surface and a soil or similar soft surface can not model the speed and acceleration/deceleration conditions relevant to high-speed cross-country travel. Thus, basic vehicle mobility processes, such as the distribution of sprocket power (energy transferred at time, *t*) between dissipative interactions (soil deformations, heat of friction, etc.) and changes in vehicle momentum, cannot be realistically modeled.

Another major weakness of the NRMM (and most other existing models) is the lack of parameters for relating operating performance under variable operating conditions to logistics requirements. As a consequence, logistics demands for fuel cannot be modeled as a function of operating performance and operating environment. Because fuel will be the dominant logistics burden for the AAN, the capability of simulating fuel consumption for alternative vehicle designs in highly mobile AAN tactical scenarios will be critical. The committee found no evidence that serious work is under way, or even contemplated, to develop models of high-speed, off-road vehicles, at either the vehicle system level or the mobility subsystem level, that would model the underlying physical processes to enable rational trade-offs based on fuel consumption. Army models for this purpose must account for diverse combinations of vehicle characteristics, tactical alternatives, and force structure options. In short, the models should treat the reduction of the largest logistics burden *as a primary design criterion.*

Since the NRMM was developed, significant advances in simulation methods have rendered the NRMM vehicle dynamics subsystem (VEHDYN) obsolete. For example, commercially available simulation software for mechanical system dynamics, software that is used extensively by the Tank-Automotive Research and Development Center (TARDEC) and the vehicle manufacturing community, can more accurately model the vehicle dynamics of the advanced vehicle concepts being considered for the AAN than VEHDYN can. This technology should be incorporated into extensions to the NRMM for AAN trade-off analyses (specific developments are discussed in Chapter 5).

Virtual Proving Grounds for Vehicles and Drivers

High-fidelity vehicle simulators with hardware (i.e., a vehicle subsystem prototype or production unit), including a driver in the simulation loop, have recently been created as "virtual proving grounds" for testing advanced mobility concepts. These simulators can be used for relatively inexpensive experiments involving human drivers, concept vehicles, alternative vehicle technologies, terrains and soils, and tactics in a realistic test environment.

With these tools, uncertainties associated with vehicle and driver performance, especially at the high cross-country speeds being considered for AAN, could be quantified and used for concept development and materiel optimization. A critical need now is to interface the results from vehicle performance models with the parameters in the virtual proving ground simulations to represent interactions between vehicle and terrain. That is, results from mobility subsystem modeling (e.g., an improved NRMM model) must be able to flow up to the soldier-and-system interactive level provided by the virtual proving ground. The capability of modeling the interactive effects of driver behavior, tactics, and variations in system configuration on fuel consumption and mobility performance measures is particularly important. Moving down the M&S hierarchy of Figure 3-1, results from the virtual proving ground experiments could be used to identify critical elements of vehicle-terrain interaction in the mobility subsystem (and critical elements in models for other subsystems, such as the situational awareness subsystems for both driver and vehicle) that require design changes to meet mobility performance goals without sacrificing fuel economy. (Vehicle modeling capabilities that would have to be extended to bring these new tools to bear on AAN logistics are discussed in Chapter 5.)

Linking System-Level Modeling with Engagement Simulations

During the past decade, major advances have been made in distributed interactive simulation (DIS), a revolutionary new capability that enables soldiers to operate vehicles in a realistic battlefield environment. The use of DIS technology to simulate operations involving unit-level AAN forces would provide a rational basis for assessing the military value of advanced mobility concepts and tactics that take advantage of revolutionary new mobility capabilities. Of course, the conceptual vehicles in a DIS experiment should realistically reflect the vehicle handling and performance characteristics (including realistic fuel consumption!) determined in the virtual proving ground (linkage upward in the M&S hierarchy of Figure 3-1). Tactics explored and developed in the DIS environment should be analyzed for sensitivity to performance of the vehicle-driver-terrain system to identify systems-level conditions and criteria that should be further explored, or even redesigned, in the virtual proving grounds (linkage to models further down the M&S hierarchy).

General Implications for Implementing an M&S Environment

Many opportunities and unmet needs remain for each of the three "mobility performance" modeling levels discussed above. However, to meet the larger need for an M&S environment to support AAN systems design with effective logistics trade-off analyses, *the M&S tools at different levels should be used to pass information up and down the structure-performance hierarchy shown in Figure 3-1*. The performance results for specific designs modeled at one level must be incorporated into initializing conditions and physical relationships represented in the models at the next higher level. The outcomes of simulation runs at one level must be analyzed into critical elements of underlying structures or functions that become the objectives or the outcomes to be avoided in designs at the next lower level.

Note that coupling between levels, in the sense that the models at two (or more levels) are run *together,* is neither essential nor, for many design issues, even desirable. Running a series of optimizing runs with a model at a given level, then feeding the lessons learned into subsequent simulations and design analyses at levels above and below in the hierarchy is usually more efficient. Iterative passes up and down the hierarchy of distributed M&S tools that can be run independently of one another are more practical than an integrated "system of models" that run simultaneously.

Mission Rehearsal, Mission Logistics Planning, and Training Applications

A hierarchical M&S environment well suited to system trade-off analyses in which logistics requirements are a primary design objective is not just a design tool. The same M&S capabilities can be used to support mission rehearsal, detailed logistics planning for specific missions, and troop training exercises. The committee identified M&S capabilities for all three of these additional functions as highly desirable for reducing AAN logistics burdens on an *operational basis* (beyond the reductions achievable by rational systems design). Indeed, if a hierarchical M&S environment were available for system trade-off analyses in a broad area—such as vehicle mobility, system lethality, or communications for situational awareness—the major problem for managers would be allocating sufficient computer time.

Trade-off Analyses for Small-Unit and Force-on-Force Engagements

A typical AAN mission scenario involves operational units employing numerous diverse systems. Unless wider performance goals (that is, the collaborative, coordinated performance of these units as functional components of a *military operation*) are brought to bear in a systematic way during design, field training, and other activities, systems could be optimized only for their mission profiles, without regard for optimizing the combined outcome of all systems participating in an operation. An axiom of systems engineering is that optimizing the performance of components does not necessarily optimize the performance of the system as a whole. In the context of an M&S hierarchy analogous to the one in Figure 3-1, engagement M&S would ensure that the performance characteristics for which individual systems are optimized derive rationally from the performance requirements for *military operations.* Each system must be considered as a component in a larger overall system.

BOX 3-4 Characteristics of an AAN Unit for Small-Unit and Force-on-Force Engagement Analyses

- Lethal force inserted and extracted by air or sea
- Logistically self-contained force
- Complete situational awareness
- Stand-off precision firepower
- Self-protection, both active and passive
- Rapid ground maneuvering

The trade-off analysis strategy should address an entire AAN mission, including the pre-injection logistics of assembling the force, transportation from the continental United States to the staging area, deployment to the battle area, mobility and engagement in the battle area, and extraction. Models in each phase of the mission should be coupled for simulations of the integrated system.

Existing models must be extended to represent the revolutionary tactics and materiel capabilities being considered for the AAN at both the small-unit and force-on-force engagement levels. Box 3-4 is a preliminary list of the major characteristics of an AAN operational unit and the interactions that must be represented in M&S tools to support AAN logistics trade-off analyses at this level. Although some characteristics of an AAN unit may be only indirectly related to logistics, every characteristic influences AAN logistics trade-offs: *everything depends on everything else.*

Existing operational M&S tools at the unit level and higher appear to be adequate to support AAN logistics and system capability trade-offs, but these tools are not linked to the engineering-level analytical tools used to assess technological alternatives. To correct this situation, the logistics and performance modeling capabilities at the Army Materiel Systems Analysis Activity (AMSAA) should be linked, via the DoD HLA, with M&S tools at the systems modeling level and lower.

The hierarchy of M&S tools in Box 3-5, shown with their proponent organizations, suggests the scope of analytical methods that would support AAN logistics trade-offs up and down the six levels shown in Figure 3-1. According to representatives of AMSAA and the ARL, the first three categories of M&S tools (the engagement levels) are generally capable of supporting AAN mobility analyses. They observed, however, that the engineering analysis tools, which are the responsibility of the various research, development, and engineering centers (RDECs), are in need of substantial development and would have to be linked with the higher level tools to provide a distributed M&S environment capable of supporting AAN logistics trade-off analyses in the vehicle mobility area. To the committee's knowledge, similar needs exist at system, subsystem, and component levels in other significant technology application areas.

Capabilities to support uncertainty and sensitivity analyses will be essential for interactions between the engagement level of analysis and the system/subsystem levels below it to ensure that realistic trade-offs are made and that decisions are based on sound data. For example, errors in a mobility performance simulation could amplify errors in the results at the engagement level. If the soil data provided to an NRMM-like model are invalid, vehicle speed predictions will be incorrect. This error, which would affect the arrival times of units at an operational area, could not only have serious tactical consequences but could also make it impossible for the unit to sustain itself for the duration of its mission.

BOX 3-5 M&S Tools to be Linked for AAN Logistics Trade-off Analysis

Simulation of Force-on-Force Engagement (TRADOC Analysis Center)

- Battlefield effectiveness
- Weapons mix analysis
- Support/logistics requirements
- Requirements trade-offs

Simulation of Fighting Unit (AMSAA)

- Small unit effectiveness
- Supply consumption rates
- Cost/performance trade-offs

Simulation of One-on-One Engagement (AMSAA)

- Weapon system performance
- Expendable consumption rate
- Technology trade-offs

Simulation of Components and Subsystems (ARL/ARO/RDECs)

- First principles performance/resource
- Consumption modeling
- Hardware/soldier-in-the-loop
- simulation
- Durability/reliability assessment
- Component/subsystem optimization
- Constraint enforcement

- Weight and volume
- Fuel efficiency
- Personnel
- Speed and agility

The fidelity of results from modeling at one level in the M&S hierarchy will not necessarily scale linearly with the analyses conducted at the next level up or down. Because of the nonlinear, dynamic nature of the complex systems being modeled at several levels in a typical M&S hierarchy, even vanishingly small errors in one model may result in significant errors in apparently unrelated models, making the entire mission simulation inaccurate. Mathematical methods of analyzing coupled models that are vulnerable to nonlinear "breakdowns" are an area that will require applied (or even basic) research. At a minimum, sensitivity analysis will be required to ensure that trade-offs are based on compatible levels of model fidelity and that they account for uncertainties in model data and physical representation.

Trade-off Analyses to Support AAN Mission Reliability

The extraordinarily high levels of operational performance desired by AAN planners must be traded off against the equally fundamental logistical objective of 14-day self-sustainment. For example, traveling over rough terrain will create enormous loads and stresses on vehicle subsystems. Unless the subsystems are designed for reliability under these operating conditions, the vehicles might not be able to remain operational for the full period of time. Analytical tools will have to be developed for designing for this extremely high level of reliability. M&S requirements to support this essential capability ("AAN mission reliability") are detailed in Chapter 7. The discussion is focused on the role of a hierarchical M&S environment in achieving materiel reliability objectives.

In the hierarchy of tools shown in Figures 3-1 and 3-2, detailed consideration of design for reliability occurs at the *lower levels of the modeling chain,* during component and subsystem design. The properties (and quantitative measures) to achieve durability and reliability are dictated by the load and stress histories for extended operation of the entire system. For new systems with unconventional designs that are required to operate in wholly novel performance regimes, these factors must be formulated as quantifiable structural requirements in the higher levels of M&S analysis shown in Figure 3-1, beginning with the engagement and DIS levels, at which operational performance begins, and translated into realistic structural requirements. As shown in Figure 3-1, operational use and load histories cascade down the left communication channel (shown as arrows between levels in the distributed M&S environment), providing data for designing for reliability at successive levels, down to the lowest level.[2]

Traditional methods of system design for military vehicles, for example, do not include the *reverse communication channel* (shown as the right arrows between levels in Figure 3-1). This channel feeds information on achievable reliability and performance at the component and subsystem levels back up the hierarchy to the operational level. System designers and war-fighters can only work together effectively at the higher levels to determine acceptable trade-offs when the results of iterated analyses indicate that all performance objectives cannot be met. The capability to iterate down and up the hierarchy is, therefore, essential to meeting reliability objectives, but this capability does not exist in current military system modeling, simulation, and design technology.

AMSAA has made a considerable effort to bring M&S to bear on designing electronic systems for reliability using *physics-of-failure* methods. Although this approach has been useful in the electronic systems domain, it is not widely accepted or used in the mechanical systems design arena. An in-depth study completed under the auspices of the National Security Industrial Association and the Computer-Aided Acquisition and Logistics System initiative, recommended a "simulation-based" approach to designing for reliability (CALS, 1989). The blueprint for technology development and implementation to support design for military mechanical system reliability was, however, never acted upon. This blueprint is still an excellent guide for technology development and implementation to achieve AAN reliability goals. AMSAA has also identified a need for the Army to use methods based on what the committee refers to as "mechanisms of failure" to design mechanical systems and subsystems for reliability. The conceptual relation of physics-of-failure modeling in electronics to the more general use of mechanisms of failure for reliability engineering of AAN systems is discussed in Chapter 7.

An adequate systems design environment to meet the goal of 14-day self-sustainment will require significant development and integration of engineering-level M&S tools, as well as technology developments of dynamic-system simulation tools for load prediction and of stress analysis tools for failure prediction. The Army's most urgent need, however, is for integration of these tools into an *interactive environment that enables rational trade-offs among reliability, operational capability, and sustainment.* In some instances, integration will mean tight coupling, in which the coupled models are run together. In other instances, the integration will mean allowing for the easy and consistent transference of results (for initializing and bounding conditions, establishing parameters and other data) from one model to another.

This point was illustrated in the section on mobility trade-off analyses. Transforming load histories rapidly and accurately into *reliable* subsystem and system designs, will require a concerted effort to link state-of-the-art computer-aided

[2] Appendix C and Chapter 7 describe how this flow of structural and performance requirements (for reliability or other fundamental system objectives) can cascade to levels of materials selection and, in longer-term projects to achieve difficult performance requirements, even to M&S applications for designing materials with novel microstructures and nanostructures. Conversely, information on materials alternatives developed at lower levels will be fed up to the materials choices used in the design of components, at the lowest level shown in Figure 3-1.

engineering M&S software with virtual proving ground simulators. These designs can then be communicated upward to the operational simulation arena (engagement M&S), where performance of the designs can be assessed. Loads based on realistic projections of operational use can then be evaluated and communicated back down the hierarchy to assess and improve reliability at the engineering levels of design analysis.

The capability for designing reliability into a system using hierarchical, linked models of structure-function relationships has already been implemented and used effectively in designing electronic systems. Success in modeling and simulating the physical processes and causal structures that underlie functional relations and capabilities at all levels of the design hierarchy for electronic systems is in part a reflection of the relative simplicity of the structure-function relationships, compared with the far more complex relationships underlying mechanical reliability in military platforms (ground and air vehicles, lethal systems, etc.). Furthermore, much more investment has been made in developing M&S tools to design highly reliable electronic systems, especially computer systems, than for tools in designing the mechanical aspects of military systems.

FACILITATING A MODELING AND SIMULATION ENVIRONMENT TO SUPPORT SYSTEM TRADE-OFF ANALYSES

The Army will have to establish the foundation for trade-off analyses and validate it through constant application to problems relevant to the AAN over the next four years to have any chance of completing systematic exploratory engineering of the feasible subsystem and component-level design options before 2010. Therefore, development and integration of the M&S capabilities that can support trade-off analyses must be initiated immediately. In the face of competing interests and program inertia, the Army may have to establish a programmatic mechanism to coordinate and realign existing activities and maintain a strong focus on the overall environment. One way to accomplish this would be to establish a *strategic technology objective* that had strong support and continuing oversight from senior war-fighters committed to the AAN process. In this section, the committee suggests how the Army can facilitate integration, improvement, and development of M&S tools. While Army operational and engineering details differ from those encountered in the commercial manufacturing sector, the considerable experience gained there can be exploited to integrate M&S tools.

Box 3-6 lists key elements for implementation. At the outset, the Army set its priorities for the M&S tools needed to meet AAN requirements. The Army should adopt an evolutionary approach to developing and applying the M&S technology base. Many of the elements required for AAN logistics trade-off analyses already exist, but past attempts "to start with a clean sheet of paper" and create the "mother of all models" have failed.

BOX 3-6 Facilitating AAN Logistics Trade-off Analyses

- Define priorities for M&S development to meet AAN needs
- Secure buy-in and commitment from others
- Focus on AAN logistics trade-offs
- Continuously develop tools and technology based on need
- Validate models based on rapid prototype testing

Setting Priorities

The Army should focus its limited resources on the following tasks:

1. Define the modeling environment and tools necessary for the AAN systems designs to be developed first (i.e., tools for engineering and manufacturing development to begin around 2010).
2. Identify useful existing tools.
3. Integrate existing tools using the DoD HLA.
4. Apply the M&S tools to specific high-priority logistics trade-offs.
5. As shortfalls in existing tools are identified, develop the missing capabilities.

The architecture of the modeling system details how various parts of the models share information on all simulation elements, including data and representations related to logistics burdens and benefits. Information on logistics consequences, as well as other AAN performance objectives, must be able to travel up and down the modeling hierarchy of Figures 3-1 and 3-2 in order to fully integrate those objectives into the decision-making process. The M&S systems must be designed to be upgraded incrementally as new knowledge is gained regarding performance and logistics trade-offs. Managing this process will require a dedicated and capable program manager.

Securing Buy-in and Commitment from Others

The Army should collaborate whenever possible with organizations that have similar interests. Although the analysis technology for high-speed cross-country mobility may be beyond the interests of the sport utility vehicle and conventional on-highway vehicle manufacturing community, for example it may interest construction, agricultural, forestry, and mining equipment manufacturers. This common interest could be the basis for a joint DoD-industry technology development program to meet the needs of both the AAN and the development goals of the commercial sector. Agricultural and construction manufacturers have been leaders in the development and application of computer-aided engineering (CAE) tools and have shown great interest in virtual proving grounds. Because of budget constraints, they have shown a remarkable willingness to work with their own major competitors to create the basic M&S capabilities they all need to remain competitive in the global market.

Focusing on Logistics Trade-offs

The Army must focus squarely on AAN logistics trade-off analysis. For the recommended exploratory development program to bear fruit, the necessary capabilities can be built on the extensive existing infrastructure, which includes models developed by the defense community and M&S tools developed by commercial enterprises, existing and developmental virtual proving ground simulators, and the DoD DIS (distributed interactive simulation) environment. These assets represent an investment of many millions of dollars. With a moderate, well managed development program focused on the integration of available tools, the Army can take advantage of past investments to meet AAN design and analysis needs.

The best way for the Army to focus on AAN needs is to apply these tools to the most pressing trade-off challenges from the very beginning. A considerable effort will be required to integrate engineering and operational simulation tools using the DoD HLA. Missing capabilities can be identified through a systematic process of logistics-driven analyses. In the creation of new models and analysis tools, the Army should only invest its limited resources when deficiencies become apparent. New tools must be continually applied, tested, and validated via rapid prototyping for technology demonstrations. The involvement of soldiers in AAN war games, exercises, and interactive testing of prototypes of advanced systems will be critical for focusing M&S development on evolving AAN materiel and logistics support needs. The integrated idea teams and AAN war games that are part of the AAN process are excellent mechanisms for guiding the improvement and use of analysis tools.

The committee's emphasis on focused management of M&S in support of AAN was reinforced by a recent finding and recommendation by the Army Science Board (ASB, 1997), which pointed out the discrepancy between the Army's numerous, but uncoordinated, attempts to develop and use M&S to support Army programs, and the strong focused management necessary for these attempts to realize their full potential. The committee strongly encourages Army leadership to make focused management of the recommended exploratory development program a high priority.

At the same time, the Army should pursue basic research in several areas with the potential for significantly affecting AAN logistics. These high-priority research areas are discussed in Chapters 4 through 7.

SCIENCE AND TECHNOLOGY INITIATIVES TO REDUCE LOGISTICS BURDENS THROUGH TRADE-OFF ANALYSES

The committee concluded that the Army must make use of system trade-off analyses, beginning with the conceptual design phase, to ensure that AAN systems fielded in 2025 meet the objectives for reducing logistics burdens. The committee recommends that the following areas of scientific research and technology development be pursued to ensure that the trade-off analyses are both efficient and rational. The order of the numbered items reflects a rough order of priority.

1. Strategic Technology Objective for the Development of Distributed Modeling and Simulation Environments to Support Logistics Burden Reductions. An effective operational AAN force by 2025 will depend on critical decisions being made on materiel concepts and technologies to be used in system designs. The trade-offs in design and technology options must consider logistics burden reductions as a primary objective. Given the complexity of the decisions, the range of possibilities, and the tight constraints on resources and schedules, the best chance of meeting the target date without sacrificing AAN program goals will be analytical approaches that are fully supported by M&S tools.

Many components of this M&S capability already exist, especially in the areas of engagement simulation and mobility performance. But these components are not linked. In a coherent M&S environment, results at one level must flow upward and downward iteratively in a hierarchy from force-on-force engagement simulation at the top to engineering analyses that support the design of components and structures at the bottom (see Figures 3-1 and 3-2). Important components of this hierarchy are missing, and a few of the existing pieces can not incorporate key logistics sustainment issues in their simulations or interact effectively with the tools above or below them.

Validation of models for use in AAN trade-off analyses, both those that exist and those will have to be developed, will require continuous attention. Test data on military and commercial equipment similar to the equipment envisioned for the AAN should be used as much as possible to help validate AAN models. As prototypes of systems and subsystems targeted for AAN use are fabricated and tested, systematic experimentation should be planned specifically to validate models.

Establishing and maintaining a strong strategic focus on the overall M&S environment will require that the Army establish a programmatic mechanism, perhaps a strategic technology objective, to manage a vigorous program for AAN M&S development, applications, and validation. The committee identified three focus areas where the development of M&S capabilities will be critical to system decisions in the next decade: high-speed cross-country mobility, materiel mission reliability, and small unit and force-on-force engagement. These and other applications are described in Chapters 4 through 7 and Appendices C through F.

2. Basic and Applied Research to Improve M&S Capabilities. Although a distributed M&S environment for key near-term decisions on AAN systems can be implemented largely through exploratory development, the implementation and application of these M&S capabilities should provide the basis for prioritizing the Army's research needs. Applied research should be directed toward filling gaps in the M&S-supported analyses. If applied research cannot fill these gaps, basic research initiatives should be supported. Although most of the payoffs in terms of technology insertion into AAN systems and materiel, either from applied or basic research, are likely to materialize after 2010, this research will be vital for the Army's technological dominance beyond 2025. In addition, there will probably be some research breakthroughs that will either affect design decisions before 2010 or can be engineered into systems undergoing development between 2010 and 2025.

Mathematical tools for assessing the propagation of uncertainty and errors in distributed modeling environments, particularly in nonlinear dynamic relationships, is one example of a research need. Others are identified in Chapters 4 through 7 and the appendices.

4

Fuel and Energy

Fuel and ammunition constitute the major share by weight and volume of materiel consumed by deployed forces. This chapter is concerned with the efficient provision and effective use of fuel as a fundamental energy resource for an AAN force. The significance of fuel and energy as logistics burdens cannot be overemphasized. For an Army heavy division, fuel accounts for 70 percent of the weight of re-supplies; even for light divisions, fuel accounts for around 30 percent (Mann, 1997; Petrick 1990). Moreover, the availability of fuel (through resupply lines) dictates the tempo of battle.

An AAN battle force to minimize the dependence on resupplied energy[1] must be as energy efficient as possible. There are three logical approaches for the battle force to meet its energy needs: to increase the total energy supply, to decrease the total energy demand, or to increase the efficiency of energy utilization and management. These three nonexclusive approaches are discussed separately below.

INCREASING THE ENERGY SUPPLY

A fuel is a substance that stores energy in a readily usable form. Because energy cannot be created, the supply of stored energy (fuel) available to an AAN battle force can only be increased in two ways.[2] Either more stored energy (more fuel) can be transported to the battle force, or energy from a source material available at the staging area can be converted to a stored form of energy (fuel) usable by the battle force. The challenge is to perform one or both of these operations without increasing other logistics burdens in the process.

One strategy for transporting more stored energy is to transport a fuel that has a higher energy density (more energy per unit mass of fuel). The same amount of energy (or more) can then be supplied to the battle force for a given weight and volume of fuel. The committee reviewed two candidates for increasing energy density: hydrogen and nuclear fuel. Although both have a higher recoverable energy per unit mass than

[1] The related but distinct issue of electric energy management (i.e., optimal design of electric power transmission lines, generators for power conversion, switching gear, and electrical energy storage) was covered extensively in the *STAR 21* study (NRC, 1993a).

[2] Of course the law of energy conservation (energy can be converted from one form to another but cannot be created or destroyed) holds true for nuclear reactions and high-energy physics only if matter is understood as a "condensed" form of energy, in accordance with the relation between energy E and mass m: $E = mc^2$. This reminder is relevant to the energy supply for AAN missions if nuclear energy is considered as a source. The energy from a "nuclear fuel" comes from converting a tiny amount of the mass in the nucleus of an atom into a huge quantity of other forms of energy, some of which could eventually be converted to the electrical output of a reactor-generator system.

petroleum fuels, there are also significant complicating factors, including associated logistics burdens. For reasons developed in later sections of this chapter, neither of these candidate fuels *by itself* offers a plausible alternative to the traditional fuel supply system, which is based on transporting and consuming refined petroleum fuels.[3]

The inherent difficulty in the second approach, producing fuel from available materials, is that it requires a large source of energy near the point of use to convert the source material into fuel. In special situations (e.g., during the Persian Gulf War, when large reserves of crude oil and the refineries to convert them to usable fuels existed in the theater), a battle force may already have a primary energy source and the means of converting it to fuel at the staging area. In most cases, though, the energy source and the conversion facilities must be transported at least to the staging area, which creates another set of logistics burdens. In short, the second approach cannot be depended on for all AAN mission scenarios unless it also includes the first approach—transporting an energy source with far more energy for the weight and volume than petroleum fuels have.

The committee considered a strategy that not only combines both approaches but also might overcome the obstacles to the use of nuclear and hydrogen fuels, *provided that* a number of unsettled issues can all be resolved favorably. In this high-risk, but very high-payoff, strategy, stored energy in the form of nuclear fuel would be shipped to the staging area where lightweight, modular, transportable nuclear power plants would convert it to electrical energy. The electrical energy would then be converted by electrolysis of locally obtained water to stored energy in hydrogen, and hydrogen would replace petroleum fuels as the principal battlefield fuel for the AAN force. The obstacles to success of this strategy illustrate why increasing the energy supply is not the best approach to reducing logistics demand.

A coupled nuclear-electric-hydrogen fuel supply system depends on technologies associated with using nuclear fuels and hydrogen fuel. The component technologies are discussed in detail below to clarify the comparative advantages and disadvantages of the coupled fuel-system strategy.

Of the conventional hydrocarbon fossil fuels (oil, coal, natural gas, and their distillates and derivatives), diesel fuel (JP-8) has the highest energy content per unit volume. JP-8 is at least competitive with other fossil fuels and is better than many in terms of energy content per unit weight. The strategic, operational, and tactical logistics of using diesel fuel have been proven in war and in operations other than war for more than half a century. Diesel fuel is, therefore, a reasonable baseline against which to compare alternative fuels for the AAN battlefield and the logistical systems alternative fuels may require.

Hydrogen as a Battlefield Fuel

Storage Problem

Interest in hydrogen as an alternative to diesel fuel is based on its very high energy content per unit weight (33.2 kwh/kg versus 12.8 kwh/kg for diesel fuel), which means that, *considering fuel weight only,* hydrogen offers the same energy as diesel fuel

[3] JP-8—essentially diesel oil—is the standard battlefield fuel. The ideal is to have a single battlefield fuel to simplify logistics.

at 38.5 percent of the weight. In practice, this reduction in logistics burden cannot be realized because even highly compressed hydrogen gas occupies a larger volume than the same weight of diesel fuel and requires a heavier and larger tank, resistant to hydrogen embrittlement, to hold it safely. Cryogenic storage of liquid hydrogen also creates a large burden in container weight, as well as the safety risks of venting hydrogen gas.

In one study, the weight of a vehicle storage tank for 6.8 kg of liquid hydrogen was estimated at 42 kg (Kuhn et al., 1996). An advanced storage tank for gaseous hydrogen made of carbon-graphite composite wrap with plastic liners is estimated to weigh 6.25 kg per kilogram of stored hydrogen.[4]

Even assuming a 50 percent reduction in storage weight by 2025, liquid or gaseous hydrogen and storage tanks equivalent in energy content to 500 kg of diesel fuel would weigh about 792 kg (192 kg of hydrogen plus 600 kg for the tank). In addition to the weight disadvantage, the hydrogen system would occupy 6.1 times the volume (about 585 $cm^3/kW \cdot h$) of its diesel fuel equivalent (96.3 $cm^3/kW \cdot h$) respectively, assuming compressed gas stored at 1,000 atm.

Storing Hydrogen at Moderate Pressure in an Absorbent Material

The conventional methods of hydrogen storage assumed in the preceding discussion are based on either increasing pressure (compressing hydrogen gas) or decreasing temperature (liquefying hydrogen) to decrease the volume required to store a given weight of hydrogen "fuel." Significant progress has been made in the small-scale storage of hydrogen, at much lower pressures than those used for compressed gas, to replace a heavy battery with an efficient proton exchange membrane (PEM) fuel cell. The hydrogen is absorbed into a material for which it has a high affinity but from which it can be released at a usable rate when the pressure is reduced (to atmospheric pressure). Metal hydrides have thus far been the most successful medium for storing hydrogen in this way.

Metal hydride storage technology for hydrogen is becoming competitive in weight and cost efficiency with rechargeable batteries for some soldier-portable equipment (such as radios), but the energy density is far from competitive with diesel fuel for battlefield fuel requirements. It would take a major breakthrough in the amount of recoverable hydrogen stored in the absorbent material per unit weight and unit volume of the storage *system* for hydrogen fuel to be competitive with diesel fuel.

Some preliminary, and still controversial, research suggests that a revolutionary breakthrough is possible that would enable the storage of nearly pure hydrogen at extremely high densities in a lightweight package. A new form of carbon "nanotubes" are reputed to hold up to 50 percent hydrogen by weight (at or above the density of liquid hydrogen) and at room temperature and 136 atm (Matthews and Fedkiw, 1997). By comparison, state-of-the-art metal hydride storage systems typically hold only about 1 to 5 percent releasable hydrogen by weight!

Several laboratories, including at least two in Europe, are working on safe, high-density storage. Hydrogen could compete with petroleum-based fuels as the standard fuel provided that *all of the following conditions can be achieved through further research and development:*

[4] This estimate includes a safety factor of 1.5.

- The storage technique or a similar concept can be scaled up to practical quantities (for battlefield vehicle range between fuelings).
- The performance parameters reported in this preliminary work—density, temperature, pressure, and percent hydrogen by weight—are maintainable in a storage system that can be scaled to meet the fuel needs of AAN vehicles.
- The stored hydrogen can be easily extracted (reversal of absorption) and the storage medium reused for many cycles.

Although this breakthrough in hydrogen storage might make hydrogen more competitive with diesel fuel *on the battlefield,* transporting the hydrogen to a suitable vehicle refueling site (an AAN staging area, for example) would remain an issue.

Producing Hydrogen Fuel on Site from Water

A potential advantage of hydrogen as a fuel is that it could be produced from locally available water by electrolysis *if there is an energy source for the electrolysis.* By the year 2010, an estimated 90 percent of the world's population will be living in coastal regions, and the percentage is likely to increase by 2025 (Delmonico and Story, 1997). If one assumes that the AAN staging area would be situated on a coast or near an estuary or other large body of water, the local water supply could provide a nearly inexhaustible source of hydrogen for an AAN force. If the energy source for electrolysis, plus the systems needed to convert it to energy stored in hydrogen fuel, could be transported to the staging area with less of a logistics burden than transporting the equivalent amount of diesel fuel, then the *strategic* logistics burden of supplying an AAN force with fuel could be reduced, as well as the *operational and tactical* burdens.

Nuclear Fuel for Transportable Power Plants with High Power Density

Energy density is the fundamental reason for considering hydrogen as an alternative to fossil fuels. Based on the enthalpy of combustion, a kilogram of hydrogen has the theoretical potential to supply 33.2 kW·h of energy, compared with 12.8 kW·h from a kilogram of diesel fuel. Yet this threefold advantage pales when compared with the theoretical energy density of a nuclear fuel, which is around 2,800 kW·h/kg or *more than 80 times the energy density of hydrogen* (Paur, 1997). In fact, the principal logistics burden in using nuclear fuel is not the weight of the fuel but the weight (and other burdens) of the system that would derive usable energy from it. This section discusses whether a "ready to run" nuclear power plant could be transported to an AAN staging area and, if so, what the logistics burdens would be.

Nuclear reactors as energy sources are not viewed favorably in the United States for safety, economic, and environmental reasons. Yet the safety concerns are not insurmountable, and the economics of supplying energy for an AAN battle force are different from those of a commercial power plant supplying the national electrical grid. Two industrialized countries, Japan and France, rely heavily on nuclear power to supply their national electrical grids and have experienced no major problems.

The Navy has used nuclear powered vessels (submarines, cruisers, and aircraft carriers) since 1954 without major incidents (Suid, 1990). The Army even had a nuclear power program in the 1960s, which was also run without incident. The reasons given for terminating the Army program were that (1) there were no major cost savings for nuclear power over petroleum-based fuels in the Cold War mission scenarios of that era, and (2) there was no operational requirement at that time for an unlimited supply of fuel within operational distance of the battlefield (Suid, 1990). The very different mission scenarios that have led to the AAN battle force as a concept of operations for first-in forces suggest that it is time for the Army to reassess the nuclear option as a primary energy source.

Several technological developments since the 1960s have brought fieldable nuclear reactors closer to realization. The compact nuclear power source (CNPS), developed by Los Alamos in 1987, tackled many of the technological problems associated with fielding a lightweight nuclear reactor: portability, up to 18 months of unattended operation, a 20-year cycle time between refuelings, absence of weapons-grade material, operation under harsh environments (280 km/h winds, -50°C temperatures), and "walk-away safe" system design (i.e., minimal risk to the environment or local population, even if no action is taken during an accident) (Los Alamos National Laboratory, 1988). The 20-kW power output of the current generation of CNPS reactors is not on the scale of the projected power requirement for an AAN battle force of 88 MW.[5] Still, the field ruggedness of CNPS technology is worth examining for applicability to designs for centralized power plants with high energy densities. (The option of dispersing lower wattage nuclear power plants on the battlefield was not consistent with the AAN operational concept and was not evaluated by the committee.)

For the purpose of analyzing the logistical implications of the nuclear power option at a rudimentary level, the committee assumed that nuclear reactor modules for producing electrical energy from the primary nuclear fuel source would be available in the AAN time frame with effective power densities of 0.4 kW/kg. Although they have never been built, there appear to be no technological barriers to building modular, scalable plants in the 10 to 100 MW range with this power density (NRC, 1989; Angrist, 1982). The exploratory discussion in the next section is based on this assumption.

Coupled Nuclear-Electric-Hydrogen System

Generating hydrogen from locally available water would have logistical advantages for a primary battlefield fuel, assuming that the revolutionary technology for safe, high-density storage of hydrogen can be realized. The primary energy source for producing hydrogen on site could conceivably be a transportable, modular, nuclear power plant. In effect, a fraction of the energy released from nuclear fission would be converted to electrical energy, a fraction of which would then be converted to chemical energy stored in the hydrogen. If AAN battlefield systems use fuel cells (which convert stored energy in a chemical fuel to electricity) as their primary energy conversion device, hydrogen would be a convenient battlefield fuel because the proximal fuel for fuel cells is hydrogen (see Box 4-1). AAN systems that use internal combustion engines could also burn hydrogen fuel, although their energy conversion efficiency would probably be less than systems that use fuel cell conversion.

[5] The derivation of the estimate of nominal power output is contained in the section on "Coupled Nuclear-Electric-Hydrogen System" that follows.

To illustrate the scale of this coupled nuclear-electric-hydrogen energy system and the issues involved, the committee developed the following rough estimate of the reactor capacity required for an AAN battle force unit of 8,000 troops.

BOX 4-1 Fuel Cells

A primary advantage of using a fuel cell over a combustion engine to power an electrical generator is that the fuel cell can convert more of the stored energy in the fuel to electrical energy. Fuel cells have been used for more than three decades in space applications, and they are being considered for use as residential and commercial electric power generators, as well as generators for electric vehicles. The focus of recent research has been on developing compact fuel cells that are weight- , volume- , and cost-competitive with traditional power sources, including batteries. Fuel cells are categorized generally by electrolyte and operating temperature, from solid-oxide fuel cells that operate at 1,000°C to proton exchange membrane and direct methanol fuel cells that operate at 25-90°C. Current research is focused on reducing the cost and complexity of fuel cells powered by hydrocarbon fuels through more active electrocatalysts, lower cost materials of construction, and the development of fabrication processes suitable for mass production (NRC, 1997a).

In a 1987 report, the Army Science Board estimated that a light division of 10,277 troops would consume 165,000 kg (165 metric tons) of fuel per battlefield day (ASB, 1987).[6] Assuming a lower heating value of 12.8 kW·h per kilogram of diesel fuel, this fuel consumption corresponds to an energy requirement of 2,110 MW·h. Prorating this estimate for an AAN battle force of 8,000 troops gives a ballpark estimate of 1,640 MW·h for the daily energy required, or an average power demand 68.5 MW.

Assuming peak power does not greatly exceed the average and a 78 percent conversion efficiency for converting electrical power to hydrogen, an 88-MW nuclear reactor would be required to produce enough hydrogen to meet the energy needs of the nominal battle force. Using the committee's estimate of 0.4 kW/kg for a nuclear power plant in the 10 to 100 MW range, this nuclear power plant would weigh about 220 metric tons and would have to be modularized for shipment to the staging area.

The weight of the electrolysis unit, which would produce hydrogen from water, must be added to the weight of the power plant, which converts the nuclear energy to electrical energy. Based on today's commercial technology, an electrolysis unit weighing 100 metric tons produces about 75 kg/h of hydrogen. The 68.5 MW of power translates to a hydrogen production rate of about 2,100 kg/h, which means 28 units would be needed. With today's electrolysis technology, then, the weight of the total nuclear-electric-hydrogen energy supply system would be 3,020 metric tons. The AAN battle force's mission would have to last 19 days for this weight burden to break even with the strategic logistics burden of transporting diesel fuel.

The break-even point improves considerably if one anticipates that a more efficient electrolyzer can be developed based, perhaps, on the same technology as fuel

[6] The figure in the report was 57,000 gallons of POL (petrol, oil, and lubricants). For simplicity, the committee has converted this amount to kilograms and assumed a slightly rounded-down amount as the fuel component. Data for both light and heavy units show that the ratio of troops to vehicles (both ground and air) has remained relatively constant, at about 4 to 1. Proration on the basis of relative troop size is, therefore, reasonable.

cells for vehicles. The U.S. Navy is already working to reduce the weight of H_2O electrolyzers used on submarines. The weight of an electrolyzer unit could probably be reduced by at least a factor of 20, to about 5 metric tons apiece. Then the ensemble weight (nuclear power plant plus advanced electrolyzers) becomes a more manageable 360 metric tons, or about the weight of 2.2 days' worth of diesel fuel. Any AAN operation that lasted more than three days would then have an increasing advantage in reduced strategic logistics burden with the coupled energy system (Figure 4-1).

This simplified analysis does not take into account the risks of going into a military operation with only one primary source of power, which might be vulnerable to attack, sabotage, or accident. If two 88-MW units were used, the crossover point for payoff would increase (although by less than a factor of two, because there would not have to be twice the number of electrolysis units). Another possibility is that a number of smaller reactor modules might be used at the storage area, with a smaller safety margin to cover the loss of one or two. (The same approach could be taken with spare electrolysis units.)

Even if the assumptions in the estimate are changed, this exercise illustrates several important points. First, a realistic approach to increasing energy supply while decreasing logistics burdens must take into account the entire system, from the materiel that must be transported to the staging area (the strategic logistics burden) to how AAN vehicles are powered and refueled (the operational and tactical burdens). Second, an energy system based on a single petroleum fuel (e.g., diesel fuel) is tough to beat without going to a more complex system (such as the coupled system discussed here) and

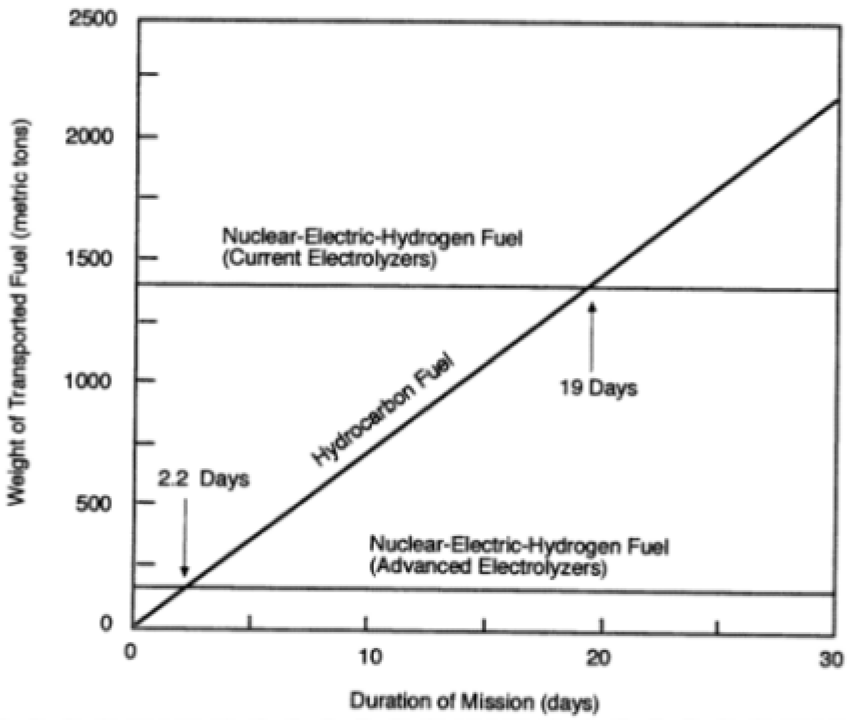

Figure 4-1
Alternative energy systems for the AAN.

making radical changes in many areas. Third, although the coupled nuclear-electric-hydrogen system has the potential to reduce fuel burdens substantially and appears worth evaluating, a significant number of research breakthroughs and technology developments, especially in safe, compact and lightweight means of hydrogen storage, would all have to fall into place. Finally, the committee believes that the most important lesson to be learned from this analysis is that *reducing energy demand* is a far more dependable strategy for meeting AAN energy needs than gambling that unrestrained energy demand can be met by increasing the energy supply. If the gamble did pay off, reducing energy demand without sacrificing other performance characteristics would make a radical alternative like the coupled nuclear-electric-hydrogen system easier to implement.

REDUCING ENERGY DEMAND

The principal consumers of fuel in an Army division are vehicles. Reducing energy demand thus amounts to reducing the vehicular demand for fuel. In 1993, the Office of Transportation Materials reached the conclusion that "the current, most successful method for improving fuel efficiency is to reduce the weight of automobiles" (DOE, 1993). This principle can be extended to all vehicles. The most direct way to reduce energy demand is to *reduce the weight* of vehicles.

Four strategies for achieving this goal are explored in this report. The first is to develop a suite of minimally crewed or autonomous (unmanned) vehicles for the AAN battle force. This would reduce the large volume (and hence large weight) associated with larger crews. This strategy is detailed in Chapter 5. A second strategy is to replace currently used materials with materials that provide equivalent performance (toughness, strength, etc.) but weigh less. The third strategy is to select materials and design vehicle components and subsystems for optimized system performance. ("System performance" in this context includes fuel efficiency and other reductions in logistics burdens, as well as the traditional objectives of survivability and crew protection.)

Fourth, incremental improvements can be attained with "low tech" solutions that affect how a vehicle is used rather than how it is designed or what armament and protection it carries. Idling discipline, towing vehicles, route selection, and fuel economy mandates during procurement were identified in two Army Science Board studies (ASB, 1984; ASB, 1987) as areas for reducing fuel consumption. The committee found little evidence that the Army has acted on these recommendations.

Lighter Vehicles through Materials Substitution

Vehicle fuel consumption is directly correlated with vehicle weight. The most likely candidate materials for reducing vehicle weight in the short term (primarily light but expensive substitutes for steel) are alloys of titanium, aluminum, or magnesium. The relative weight savings are approximately 43 percent, 66 percent, and 78 percent, respectively, when these alloys can be used instead of steel (see Table 4-1). However, density (mass per unit volume) alone is not the deciding factor in selecting a material for a given application. A more precise design parameter is usually a material property critical to the demands of the application, such as stiffness (modulus) per unit mass or yield strength per unit mass[7]. Nevertheless, density (mass per unit volume) is often a useful initial indicator for assuring materials with broadly similar properties (such as metals) (Ashby, 1992).

TABLE 4-1 Densities of Elements That Form the Basis of Major Structural Alloys

Element	Theoretical Density (g/cc)	Density Ratio Relative to Steel
Be	1.85	0.22
Mg	1.74	0.24
Al	2.70	0.34
Ti	4.54	0.58
Fe (steel)	7.87	1.00
Ni	8.90	1.13
Cu	8.96	1.14

Across-the-board incorporation of lightweight materials into Army vehicles will require three key advances: a decrease in the cost of lightweight materials, an increase in designer awareness, and accelerated development and empirical verification of new lightweight materials through M&S at the atomic and microstructural levels.

Decreasing the Cost of Lightweight Substitutes

The near-term incorporation of lightweight materials into Army vehicles will require that their cost be reduced. At present, known substitutes that could substantially reduce vehicle weight are 3 to 30 times more expensive than the steel equivalent. The high cost for lightweight metal alloys of titanium, aluminum, and magnesium reflects one or two factors: the cost of extracting and refining the metal from the raw ore and the cost of processing the metal into its final shape. The auto industry, which is well aware of these cost obstacles, is attempting to promote strategies among its suppliers to lower the cost of extracting, refining, and processing these metals, particularly magnesium (DoC, 1995; Sherman, 1997). The Army can monitor developments and promote its requirements through continuing participation in programs involving industry, such as the Partnership for a New Generation of Vehicles (PNGV) and other venues.

Non-metallic alternatives should be considered. The ceramic-organic hybrid composite armor developed for the composite armored vehicle prototype, exemplifies the potential of novel ceramic materials. The cost of composites is relatively high in limited quantities, and it would be useful if manufacturing and production trade-off studies were made comparing the cost of composite armors and metallic armors in large volumes.

In evaluating alternatives, the cost-performance trade-off analyses should assess life-cycle costs, not just the up-front acquisition costs. (See discussion of life-cycle cost

[7] Yield strength, σ / ρ, is an excellent design parameter for a stationary metal component. If the specific application for the component involves moving parts, where inertial forces become important, a more precise design parameter derived from the yield strength would be $(\sigma)^{2/3} / \rho$.

models in Appendix C.) When life-cycle costs, including relative fuel costs, are used to compare materials options, increases in fuel efficiency alone from using lightweight materials would justify their use in some applications, even with high up-front costs.

Information Resources for Improving Materials Selection

A second obstacle to the Army's use of lightweight materials is the lack of awareness by system designers of the existence and properties of new alloys and other advanced composite materials. Materials that are not known include materials developed secretly by the former Soviet Union, such as aluminum foam and explosive armor coatings. Software that mines the internet for data can be useful in carrying out searches for information on novel materials. Often, the material selected for a particular application is the material the designer is most familiar with, either from prior experience or from engineering handbooks rather than the best material for that application (Ashby, 1992).

Although the Army already participates in many networks for research on new materials and applications development, it should not overlook the research activities of the other services. The commercial industrial sector, as well as the other services and defense agencies, would also have much to gain from developing better information resources. Therefore, the Army should leverage its resources in this area by encouraging and participating in partnerships and networks that would give systems designers and engineers at all stages in the development, testing, and acquisition process access to the best available information on less well known materials and compare them with commonly used materials. The Army will also need tools to help designers select from and understand this wealth of information; the development and widespread adoption of these tools could be encouraged through the same partnerships and networks.

Modeling and Simulation Aids for Designing Materials

Appendix C explains the long-term potential of M&S technologies for designing and evaluating new materials and for developing new ways of structuring known materials. M&S technologies will also contribute to the Army's search for substitute materials that could reduce the weight of vehicles while maintaining or improving other critical properties. The functional properties of a material can be altered, controlled, and even designed by manipulating its microstructure on multiple spatial scales, ranging from the interatomic scale (Angstroms) to the nanometer and micron scales. The timely design and assessment of new microstructures will require computer-based tools (1) to model new structures (for example, biomimetic materials that mimic properties of structures found in nature), and (2) to use structure-property relations derived from physical theory and materials engineering to predict the bulk properties of a modeled microstructure. Processing issues should be considered simultaneously to ensure that advances in materials design could be readily translated to fabrication. Integrating appropriate processing models into overall simulations will be key to using M&S tools for materials design. The importance of M&S tools for advanced materials design has also been recognized in peer-reviewed studies by the NRC National Materials Advisory Board, one of which concluded:

> . . . a more comprehensive materials system approach must be developed that incorporates materials modeling and processing considerations, and that allows designers to interact even more closely with materials developers to ensure the proper application of new materials.
> (NRC, 1993b, p. 50)

The design of materials (as opposed to the selection of materials for design) by modeling and simulation has great potential for future commercial and defense applications. Through research grants, federated laboratories, and various cooperative efforts with the academic and industrial research communities, the Army is already a participant in this rapidly developing field. Whether the technology will mature in time to contribute to the design of the first generation of AAN-era vehicles is an open question. For the long-term, however, the Army should continue to participate in information networks that can tap into this technology as it develops. The Army should also look for opportunities to participate in application-development efforts, particularly joint-service initiatives and other venues where Army contributions could be leveraged.

Lighter Vehicles through Optimized System Performance

The feasibility of designing vehicles for improved fuel economy by making them lighter has been well demonstrated by the research program of the PNGV (NRC, 1994a, 1996, 1997b, 1998; DoC, 1995). In some instances, a material with less mass per unit volume can be substituted more or less directly. Often, however, the functional role of the component or structural material has to be rethought to take advantage of an innovation that achieves the same or better functional performance by several measures, including weight reduction. Some of these weight-reducing innovations in the commercial automotive industry (including heavy trucks, passenger vehicles, and light trucks) could be adopted either directly or with modifications by the Army.

For combat vehicles the Army will have to develop its own system-optimizing approach, however, because some of the performance objectives, such as protection of the vehicle and crew from hostile action, are not major concerns for commercial vehicle designers. Traditional approaches to improving protection have tended to increase rather than decrease system weight. Innovative materials solutions that combine reduced system weight with increases in system performance will reduce AAN logistics burdens.

System Optimization of Protection and Other Vehicle Weight Reduction Factors

Protection of an AAN combat vehicle and crew must be assessed at the system level, along with other system performance goals, such as cross-country mobility, fuel efficiency, and lethal efficiency (i.e., one round, one hit, one kill). In addition, protection is itself a complex performance goal that includes survivability characteristics (such as shielding or active protection against ballistic impact, blast, heat, directed energy, and nuclear, biological, and chemical agents) and stealth characteristics (such as physical configuration and thermal and electronic signature).

If structural and protective components of a vehicle are designed with distinct structures for each function, the system will be too heavy, too large, and too unwieldy to meet AAN performance goals. Optimizing an AAN vehicle for the full range of protective objectives and other performance criteria will require designing the structural components and the entire protective subsystem for multiple functions. Light, small, agile systems that require minimal field maintenance and logistical support will have to be designed at the subsystem, component, and materials design levels for structural integrity, shielding characteristics, and signature management. Instead of providing protective elements with distinct material components, such as armor plating or appliqué, the components of the protective system will have to be multifunctional.

Similar principles apply to the design of AAN air vehicles (piloted or unmanned), soldier portable equipment, and other combat systems, as well as ground combat vehicles. For each application, the Army should consider the full range of options to select the best "system solution" to protecting the AAN battle force while meeting other objectives. Vehicles, shelters, and soldiers will need lightweight, effective protection against diverse threats. Individual soldiers will need protection against small arms fire, but their body armor must not impede their fighting effectiveness. (System-level considerations for protective systems for AAN combat vehicles are discussed more fully in Appendix D.)

EFFICIENT ENERGY MANAGEMENT

The preceding discussions on increasing energy supplies and decreasing energy demands have illustrated the advantages of using a systems engineering approach to determine the best alternatives for AAN mission scenarios. In this section, a systems approach is described for improving the efficiency with which energy, however supplied, is used on the battlefield (e.g., transporting vehicles, soldiers, ammunition, or materiel; powering information systems; and energizing weapons). The focus of this section is on *vehicle* energy management, on the assumption that a highly mobile, mechanized battle force will rely on vehicle energy systems to supply energy for anything that does not have a self-contained energy supply. (Categories of materiel with self-contained energy supplies include energetics for projectiles [discussed in Chapter 6] and compact power for soldiers [discussed in Chapter 8]).

Fuel Economy as a Functional Specification

The committee believes that the best overall approach for achieving fuel economy in Army vehicles may simply be to specify a maximum fuel consumption target along with other performance specifications to the vehicle manufacturer and allow the manufacturer to make the system trade-offs. In other words, the Army is likely to elicit a better outcome in response to a system-level *functional specification* than to a design specification. This approach would ensure that the appropriate engine (e.g., diesel, gasoline, turbine, or fuel cell) is chosen for the job and that lightweight materials are used where they are feasible and most beneficial.

In procurements of ground vehicles, the Army already uses functional specifications for some performance requirements, such as vehicle range (distance between refuelings), but no limits have been stated for the rate of fuel consumption. The committee recommends that all vehicle procurements include an unequivocal, readily measurable limitation on vehicle fuel consumption. Although this functional specification would be critical for AAN systems, it would also be helpful for procurements before 2025. A specification might read as follows:

> The vehicle will consume no more than one gallon of fuel for each three [for example] miles of travel on the Aberdeen Proving Ground level ground [for example] course and one gallon of fuel for each two [for example] miles on the cross-country [for example] course, using a defined Army duty cycle. During idling periods the vehicle will consume no more than six [for example] gallons per hour.

A functional specification like this would *ensure that the manufacturers paid attention to the rate of fuel consumption* and would force designers to consider the fuel burden as important as other military requirements. In addition, establishing a standardized test course and standardized test procedures specifically for fuel consumption would enable the Army to accumulate valid, comparable data on the fuel consumption rates of ground vehicles. These data could then be used for logistics analyses in force-on-force models, trade-off analyses, mission planning, and mission rehearsals (see Chapter 3). A similar strategy is used by the U.S. auto industry to meet its fuel economy objectives.[8] The results can be seen in the figures for "highway miles per gallon" and "city miles per gallon" posted on the window of every new automobile.

HYBRID VEHICLES

Much has been said, in the Army and elsewhere, about fuel economy in vehicles with electric-hybrid power plants. These power plants consist of a *prime mover,* such as a diesel or turbine engine, that converts fuel energy to mechanical energy, and an electrical subsystem of one or more electric generator/motors and storage devices (typically, storage batteries or flywheels) to provide electrical energy. The electrical subsystem enables the prime mover to operate at peak efficiency more of the time. It can also be designed to recover kinetic energy from the moving vehicle during braking (regenerative braking). In this report, vehicles with this kind of hybrid energy supply and management system are called "hybrid vehicles."

The committee found no reason to assume that a hybrid vehicle, which gains maximum fuel efficiency under stop-and-go driving conditions (such as those typical of a city bus), would have better fuel economy than a prime-mover-only power plant on an AAN battlefield. As far as the committee could determine, the Army has not yet determined the classes of vehicles, much less characterized the duty cycle (or cycles) for representative AAN mission scenarios. There may be other reasons for using a hybrid engine (e.g., silent watch capability or electrically energized armament), but a hybrid vehicle cannot be justified on the basis of fuel economy until the Army has a model to help determine fuel consumption during an AAN duty cycle. (See Appendix E for a discussion of the interrelationship of duty cycle and fuel economy).

The committee questions whether AAN operations favor a hybrid vehicle design. The committee found no evidence that the Army has given the relevant factors the systematic, quantitative engineering analysis this important design choice deserves. To improve the fuel economy of the vehicle as a system, a hybrid vehicle would have to

[8] The committee wishes to acknowledge the technical and conceptual contributions on this topic of Dr. Wolf Elber, director, Vehicle Technology Center, Army Research Laboratory. Dr. Elber discussed issues of fuel economy with the committee at meetings in August and December 1997.

save more in energy management efficiencies than the energy costs of the added weight of the power plant's electrical subsystem and from energy conversion losses. The efficiencies could come from (1) the operation of the prime mover, (2) the transfer of prime-mover energy to the drive sprockets or wheels and other energy demands, and (3) energy recovery from regenerative braking. An analysis of civilian-vehicle duty cycles has shown that hybrid vehicles do not break even in this balance unless the average power demand of the system in normal operation is (approximately) one-fifth or less of the peak power demand (see Appendix E).

For AAN combat vehicles to move at high-speeds over rough terrain, the average power demand of a hybrid vehicle would be substantially more than one-fifth of its peak demand. For a combat vehicle to sustain a speed of 130 km/h would require nearly full power for sustained vehicle operation (see Chapter 5). Furthermore, most of the energy would go not into recoverable kinetic energy but into soil deformations, suspension losses, and aerodynamic losses. Although these preliminary considerations are based on rough approximations and general engineering experience, they imply that the fuel economy advantage often assumed for hybrid vehicles cannot be taken for granted in the AAN context.

The point of this argument is not that hybrid vehicles should be ruled out but that systematic, detailed analyses *that incorporate the relevant factors on duty cycle and nonrecoverable energy losses* should be used to assess the potential benefits and make a rational decision. Other requirements of the vehicle duty cycle may make electric drive or an alternative vehicle configuration a better choice. For example, operational requirements for transporting troops or hardware may argue for placing the power plant and drive train components in a configuration for which an electric drive works best. If an electromagnetic gun, active protection system, or directed-energy armaments are part of the system design, which therefore would demand a great deal of electric power, a hybrid vehicle might be the best choice. In short, a rational choice of vehicle configuration is likely to depend more on the overall duty-cycle requirements of the vehicle than on fuel economy.

SCIENCE AND TECHNOLOGY INITIATIVES TO REDUCE ENERGY-RELATED LOGISTICS BURDENS

Based on the preceding analyses of the logistics burdens associated with the fuel and energy demands of AAN operations and the technological opportunities for reducing these burdens, the committee concluded that the Army should pursue the following areas of scientific research and technology development. The order of the numbered items reflects a rough order of priority.

Increasing the Energy Supply

1. **Systems Analysis of Alternative Fuel Supply Systems.** An efficient and reliable fuel supply system is critical for a modern land combat force. An investigation of significant changes in the existing fuel supply system to enable AAN operations and to decrease logistics burdens should be based on a model of the entire fuel supply system, including a realistic simulation of all significant logistics burdens and their effects on the supply system and the war-fighting organization. AAN war games have begun to incorporate

realistic modeling of fuel supply logistics at the strategic, operational, and tactical levels. An immediate objective should be to couple a fuel supply model to the fuel demands of the AAN system being used in a war game. System(s) to achieve this modeling capability could also be used for fuel system trade-off analyses, mission planning, and training exercises.

2. **High-Density Hydrogen Storage.** The Army should monitor the progress of research on high-density hydrogen storage. If new technologies can be scaled and have the potential for future applications, the Army should foster industry partnerships, a joint-service program, or another mechanism for investigating the implementation of this new technology. A reasonable next step would be applied research to determine the feasibility of using technology based on high-density hydrogen storage to make hydrogen a battlefield fuel competitive with diesel fuel.
3. **Modular Nuclear Power.** The Army should investigate the feasibility of scaling modular, transportable, field-rugged, "walk-away safe" nuclear power plants to sizes suitable for use at an AAN staging area. A key consideration is whether an energy density in the range of 0.4 kW/kg can be maintained for modules of practical size (10 to 100 MW) that meet other critical performance, safety, and reliability objectives.
4. **Fuel Cell Technology.** The Army should continue its support of research and applications development in fuel cell technology. If the investigations into the feasibility of fieldable nuclear power plants and high-density hydrogen storage *lead to favorable results,* the Army should expand its participation in and sponsorship of applied research and development for large fuel cells, perhaps through partnerships with the automotive industry. *Assuming that the prerequisite investigations into nuclear energy as a primary source and hydrogen as a storable battlefield fuel are successful,* the Army should investigate an electrochemical process for converting electrical energy to fuel energy in hydrogen (reverse of a hydrogen fuel cell).

Reducing Energy Demand

1. **Information on Lightweight Substitute Materials.** The Army should find ways, through the information and research and development networks in which it already participates, to promote and support the development of information resources that would help system designers acquire data on lightweight materials. Information resources could include industry-wide databases of materials properties and user-friendly tools, such as graphical interfaces, for selecting and comparing data on substitutes for conventional materials.
2. **Lowering the Cost of Lightweight Materials.** The ongoing development of low-cost synthesis and processing technologies to extract, refine, and process lightweight materials (e.g. magnesium) warrants the Army's close observation, involvement, and encouragement. Similarly, the Army should monitor commercial developments for lowering the cost of ceramics and organic composites. Work being undertaken with the encouragement of the auto industry should be monitored and supported, as appropriate. The Army can leverage resources by keeping abreast of progress by potential

commercial users and by promoting joint-service and DoD-wide participation with industrial and academic partners.

3. **Vehicle System Weight as a Design Criterion for Trade-off Studies.** In an ideal scenario, vehicle system weight could be reduced without sacrificing other performance objectives. However, it appears that the stringent requirements proposed for AAN combat vehicles will probably require some trade-offs between system weight and other desirable—but not mission critical—capabilities. The use of armor to protect against advanced high-velocity projectiles probably will be one of these capabilities. The general requirement of protecting combat vehicles against projectiles can be addressed in many ways and to varying degrees. The integrated, hierarchical modeling environment (discussed in general terms in Chapter 3 and more specifically for vehicle design in Chapter 5) will be essential for evaluating the many technology options for AAN vehicles and for making sound decisions on the optimum strategy for balancing vehicle weight against effective protection. The lower levels of this hierarchical modeling environment could also assist designers in evaluating candidate materials for armor building blocks and new armor architectures. Feeding these vehicle protection designs up to force-on-force simulations in the hierarchy would allow the testing of assumptions about the most effective combination of characteristics in AAN war games.

Efficient Energy Management

1. **Fuel Economy as a Functional Specification.** Faced with expensive developmental trade-offs, contractors will not design fuel economy into Army combat vehicles unless the Army specifies clear and unequivocal limits for maximum fuel consumption and holds the contractors to those limits. All vehicle procurement contracts should specify readily measurable limits on vehicle fuel consumption.
2. **System Analysis of Hybrid Vehicles.** Whether an electric hybrid power plant improves the fuel economy of a vehicle depends on the vehicle duty cycle. Based on the qualitative descriptions to the committee of how an AAN battle force would operate and a general automotive engineering rule of thumb on the kind of duty cycle in which a hybrid power plant improves overall fuel economy, it seems unlikely that a hybrid vehicle would reduce fuel consumption *in an AAN operation.* However, a quantitative analysis based on realistic modeling of representative duty cycles and the distribution of energy sinks would resolve this issue. Furthermore, other factors in system design might favor a hybrid vehicle. Once again, this decision calls for a vehicle system trade-off analysis that realistically represents the duty-cycle demands on the power plant, including nonrecoverable energy losses during prolonged, high-speed, off-road operation.

5

Operational and Tactical Mobility

The AAN will be designed to project power via a battle force in the United States that can be moved rapidly to the battle area to engage in decisive combat. The force might be moved to a staging area first or, perhaps, directly to the battle area. In either case, the force will have to move across land and water before engaging the enemy in combat. This chapter discusses the operational and tactical mobility of the AAN battle force. Operational mobility is defined as movement from the staging area to the battle area. Tactical mobility is defined as movement in the battle area. Strategic mobility, the movement of the battle force from the United States over several thousand kilometers of land or sea to the staging area, is discussed in Chapter 9.

Mobility is critical because it dictates the pace of battle and the pace of resupply. Fuel, one of the major logistics burdens, is closely linked to mobility. The capability to resupply the force depends directly on the capability of moving supplies, equipment, and personnel, as well as fuel and ammunition, to the battle area. A major objective of the AAN will be to move the battle force to the battle area and close with the enemy at speeds averaging 200 km/h, five times as fast as the speed in the Gulf War.

OPERATIONAL MOBILITY

For this discussion, the committee defined the range of operational mobility, the movement from the staging area to the battle area, as 300 to 1,000 km. Two programs that would address the operational mobility requirement are the Joint Transport Rotorcraft Program to develop an advanced transport helicopter and an advanced tiltrotor program to develop a successor to the current V-22 Osprey ("super-Osprey").

According to briefings by representatives of the ARL and the Army aviation community (Bill, 1997; Kerr, 1997; Scully, 1998), the present goals of both Army programs are to lift 15 tons (the desired maximum weight of an advanced fighting vehicle) up to 1,000 km and to consume less fuel than present Army aircraft. Meeting these ambitious goals will require more than tripling the lift capability of present Army utility helicopters or quadrupling the lift capability of the V-22 Osprey.

Many insiders are skeptical that the Army can meet these goals. For example, the chief of the Aviation and Missile Command was reported to have said that a range of perhaps 500 km, half the goal, was realizable. Increases in the fuel efficiency of aircraft engines of up to 25 percent could be demonstrated, but 60 percent, the estimate for AAN systems, would require "radical engine redesign" (Winograd, 1998).

If the Army did meet its goals and could field a helicopter or tiltrotor aircraft capable of lifting 15 tons, with a mission radius of 1,000 km and a cruising speed of

325 km/h, it could cost as much as $47 million per vehicle.[1] The Army Mobility Integrated Idea Team estimated that the fuel required for such an air carrier mission would weigh 22 tons (Bill, 1997; Kerr, 1997; Scully, 1998). Table 5-1 shows the estimated flyaway cost and flying time for several sizes of rotorcraft fleets that could transport 2,000 ground vehicles for a nominal AAN battle force.

TABLE 5-1 Battlefield Mobility Trade-offs for Transport Aircraft

Fleet Size	Fleet Flyaway Cost (billions of dollars)	Flying Time[b] (hours)
250	11.75	49.3
500	23.50	24.7
750	35.25	16.4
1000	47.00	12.3
1250	58.25	9.8
1500	70.50	8.2
1750	82.25	7.0
2000	94.00	6.2

[a] Assumes cost of $47 million per aircraft
[b] Assumes the staging area is 1,000 km from the area of operations, 2,000 ground vehicles are transported, and a cruising speed of 325 km/h

The flying time in Table 5-1 was calculated by assuming that one vehicle would be transported each trip, the cruising speed was 325 km/h, and the aircraft returns to the staging area empty (or with a minimal load). The estimates include only the time the aircraft is in the air. No time was allotted for loading, transporting, or unloading anything other than vehicles, such as fuel or other supplies. No time was allotted for refueling, crew rest, etc.

The smallest fleet in the table comprises 250 aircraft, which would cost $11.75 billion and would require more than 48 hours of continuous flying time to transport 2,000 ground vehicles to the battle area. The largest fleet shown in the table is 2,000 aircraft, which could transport 2,000 vehicles in a single six-hour trip. However, this fleet would cost $94 *billion* to build.

The JP-8 fuel required to transport the 2,000 vehicles to the battle area is 44,000 tons (2,000 trips x 22 tons/trip) for all of the fleets in the table. Assuming the deployment weight of this nominal battle force with no replenishment for two weeks is around 12,585 tons (see Chapter 2), *the fuel required to transport just the combat vehicles by air would weigh as much as three times the entire battle force.*

One could legitimately argue that this burden would be incurred in the staging area and not by the battle force and that commanders would select staging areas with ready supplies of fuel and water. Even so, the aircraft providing for the operational mobility of an AAN battle force would add to the logistics burden, and might not be affordable.

[1] The aviation community has initiated a study to reduce the unit flyaway cost of the lift rotocraft from an estimated $128 million per aircraft to $47 million.

In some scenarios, the U.S. Air Force C-17 fleet planned for strategic airlift could be used to convey the battle force from the staging area to the battle area. A single C-17 could carry as many as five 15-ton AAN vehicles, and the flying time for one round trip would be 2.2 hours. The planned fleet of C-17s will comprise 120 aircraft. Using the entire fleet would require 400 trips, or three-plus trips per aircraft, for a nominal seven hours of flying time. In other words, this C-17 fleet is comparable to a fleet of 1,750 to 2,000 rotorcraft. (The obvious obstacle to relying on C-17s for operational mobility would be the need for airfields in the battle area.)

The last Army-operated fixed-wing aircraft was the C-7 Caribou, which was based on late-1950s technology and could carry 30 passengers or a load of 5 tons. This aircraft had excellent short take-off and landing characteristics, even from unimproved air strips. The Army relinquished the Caribou to the Air Force in the 1960s, however, as part of a redefinition of roles and missions by DoD.

The Army, therefore, faces a dilemma. On the one hand, the aviation research and development domain of the Army is in rotorcraft, including tiltrotor craft. Even if planned developments are completely successful, the aircraft would not be able to meet the AAN fuel efficiency goal, and a fleet big enough for the nominal force structure and rapid operations of current AAN mission concepts would not be affordable.

On the other hand, aviation technology that would be better suited to the AAN force structure and tempo of operations has been removed from the domain of the Army's roles and missions. For example, some aerodynamic studies suggest that control of the airflow over fixed wings could increase lift significantly (Bushnell, 1998). Even if the Army undertook a program to develop or improve fixed-wing aircraft, based on existing defense policy, the Army would probably be denied permission to procure it. In short, although considerable basic and applied research would be necessary to field improved fixed-wing aircraft to meet the Army's *operational mobility* needs, the Army would find it difficult, if not impossible, to support this research and insert the results into its programs.

The capability of moving the battle force from the staging area to the mission area is the prerequisite for battle. Operational mobility will be the first essential phase of the combat and logistics operations for an AAN battle force. Even with major fiscal support, the two present Army programs for transporting combat vehicles by air have little chance of providing operational mobility for a nominal AAN battle force by 2025. The Joint Transport Rotorcraft could provide operational mobility in the range of the AAN requirement (1,000 km), but only for a much smaller force than the AAN battle force. A fleet required for an 8,000-man, 2,000-vehicle battle force would probably not be affordable, either to acquire or to operate. Unless the battle force concept can be altered to reduce the need for soldiers and vehicles on the ground, the AAN will have to depend on the Air Force and Navy not only for strategic mobility (see Chapter 9) but also for a significant part of its operational mobility. But neither of the Army's sister services is now planning capabilities that could support an AAN battle force.

TACTICAL (BATTLEFIELD) MOBILITY

AAN doctrine not only emphasizes ground mobility and agility, but also greatly increases the distances associated with tactical mobility. Combined with the objective of reducing the logistics tail, the AAN mobility doctrine exemplifies the principles of maneuvering and logistics support described by Sun Tzu in *The Art of War* more than 2,000 years ago:

> The condition of a military force is that its essential factor is speed, taking advantage of others' failure to catch up, going by routes they do not expect, attacking where they are not on guard.
> When you do battle, even if you are winning, if you continue for a long time it will dull your forces and blunt your edge. . . . If you keep your armies out in the field for a long time, your supplies will be insufficient.
> Transportation of provisions itself consumes 20 times the amount transported.
> Sun Tzu, 100 B.C.

Three generic solutions to the need for AAN tactical mobility are potentially feasible. The first is the use of aircraft. Despite the problems described in the previous section, the Army will have some rotorcraft (rotary wing or tiltrotor aircraft) that could be used to move high priority troops or supplies for critical missions. But rotorcraft have not been planned to move the bulk of a battle force on and around the battlefield as rapidly as necessary to increase the rate of advance and engagement with the enemy to an average of 200 km/h.

A second potential solution is a surface ground-effect (SGE) vehicle, such as the wing-in-ground (WIG) vehicles being evaluated by the Navy (Box 5-1). These vehicles, which are based on research begun in the former Soviet Union, operate close to a resisting surface like water, ice, or snow (Skinner, 1998; Reeves, 1998). The aerodynamic mechanisms that provide the lift are not well understood but appear to use the air flow between the vehicle and the surface for more efficient lift and higher forward speed than older ground-effect concepts for "air cushion" vehicles that propel air downward against a resisting surface. WIG vehicles might be used for tactical and operational mobility. However, the lift will first have to be better understood, which will require some basic research. Also, the feasibility of flying in and out of the SGE flight regime, to traverse broken or steep terrain must be explored.

The fuel consumption rates of WIG aircraft are estimated to be one-half to one-third of rates for conventional aircraft at comparable speeds. This could translate to a corresponding savings in the logistics fuel burden for strategic or operational airlift. In addition, the speed and capacity of WIG aircraft could enable deployment, within AAN time constraints and mission environments, of heavier materiel and ground systems than could be transported by conventional aircraft. The U.S. Special Operations Command, the U.S. Atlantic Command, and the Chief of Naval Operations Strategic Study Group have all expressed an interest in WIG technology, but fundamental research would be necessary (1) on decreasing wing loading to facilitate entering the SGE aerodynamic regime, (2) understanding the type of air flow, and (3) determining why the flight of a WIG aircraft is so quiet.

The third solution is to use ground-traction vehicles. Ideally, the AAN battle force will operate with an advanced fighting vehicle weighing no more than 15 tons, but, to provide tactical mobility for the entire force, it would also employ other ground-traction vehicles weighing 15 tons or less. The committee made a considerable effort to examine the technological underpinnings of this scenario and the obstacles and opportunities it presents. Will a 15-ton, highly mobile, ground-traction vehicle with greatly reduced logistics demand possible by 2025? If so, what would the vehicle be like? To answer these questions, the committee drew heavily on the long-term work of the Army's TARDEC (Tank-Automotive Research, Development and Engineering Center) and the Corps of Engineers Waterways Experiment Station (WES) on vehicle dynamics and the development of ground-traction vehicles.

BOX 5-1 Russian WIG Vehicles

The former Soviet Union secretly developed wing-in-ground (WIG) aircraft, also called surface-ground effect (SGE) aircraft. Their lift capability comes from an incompletely understood fluid phenomenon in which a high-pressure zone is created between a low-flying object and the surface beneath it, such as ground or water. For properly designed aircraft above a certain velocity, a high-pressure air cushion forms, which keeps the aircraft above the surface. A possible explanation is that the laminar (nonturbulent) flow of air beneath the vehicle enables it to maintain high forward speed with little effort, resulting in high fuel economy compared to more conventional aerodynamic concepts. The phenomenon can be observed in nature when large waterfowl glide effortlessly close to the water.

The aircraft developed during the 35-year WIG program were designed to fly at low altitudes over water, ice, and snow. WIG designs fall into three categories: (1) aircraft that fly by SGE at all times, (2) aircraft that fly in and out of the SGE regime, and (3) aircraft that use SGE only on takeoff and landing. Several Russian design bureaus are currently selling WIG technology commercially.

The Russians have developed this technology to the point of demonstrating large WIG aircraft, notably the Caspian Sea Monster, which has a maximum takeoff weight of 540 metric tons. This large aircraft has flown at 650 km/h (350 knots) just above a surface of water or over very level terrain. The Caspian Sea Monster was considered to be a threat to U.S. submarines and surface ships. It had four turbojet engines on each side near the nose, and up to four power-augmented ramjets on the tail.

Numerous smaller WIG craft were designed and prototyped in the former Soviet Union. For example, an early prototype of the Orlyonok (Eaglet) was about the size of a C-130, had a takeoff weight of 100 metric tons, and a payload of 13.5 metric tons. A later design for an Orlyonok (not constructed) would have carried a payload of 27 tons. Another WIG design, known as the Lun, weighed 380 tons and was considered to be a threat by Russia's Scandinavian neighbors because a fleet of 10 could have crossed the Baltic Sea with minimal radar signature in 12 minutes and deposited 5,000 troops without warning.

Although WIG craft designed after the Caspian Sea Monster were smaller, a WIG craft that could transport 2,000 metric tons was considered feasible. The Soviets pursued WIG technology for naval and military concepts to the point of test-firing a missile from the Lun. Once developed, this capability could have posed a serious threat to U.S. surface ships. A large WIG could fly at 650 km/h, undetected by radar, and launch antiship missiles. The program to develop a WIG missile capability ended when the Soviet Union broke up.

The British reportedly confirmed the SGE phenomenon when a Vulcan bomber, a 210-ton aircraft, experienced an unexpected increase in speed of 20 to 30 percent and a dramatic reduction in fuel consumption in low altitude flight (approximately 100 feet). The speed was as high as 937 km/h. Although the delta-wing geometry of the Vulcan is not optimized for SGE, the aircraft displayed unexpected endurance in this test flight.

Source: Skinner, 1998; Reeves, 1998

Wheeled Versus Tracked Vehicles

Ground-traction vehicles move either on wheels or tracks. Other factors being equal, wheeled vehicles are generally weigh less than tracked vehicles, have greater fuel economy, and require less maintenance. Tracked vehicles typically provide more robust mobility over difficult terrain, soils, and obstacles (that is, they are less likely to become stuck). Therefore, a reasonable objective for AAN is a wheeled vehicle, either manned or unmanned—provided it is demonstrably either equivalent to a tracked vehicle in mobility or "mobile enough" for a particular mission.

In many terrains, wheeled vehicles are fully capable of performing the mission; witness the large number of wheeled combat and support vehicles used by armies worldwide. In addition, many wheeled vehicles use commercial engines and transmissions and have far better fuel economy than tracked vehicles (Petrick, 1990).

Many studies have been done comparing the performance of wheeled and tracked vehicles. Choosing between wheeled and tracked vehicles has, in fact, at times been an emotional subject in Army circles. In most cases, the Army has selected the "safest" approach for combat missions, namely, tracked vehicles, even though the cost of acquisition and logistics support has been higher than for wheeled vehicles.

Previous studies have led to the generalization that wheeled vehicles are most suitable below 10 tons, tracked vehicles above 20 tons, with a gray area in between where the choice depends on operating and support costs, terrain, and logistics. Based on this general rule, a 15-ton wheeled vehicle for AAN would be the Army's preference but would not be a clear-cut choice.

M&S (modeling and simulation) can yield some insights into the advantages and disadvantages of wheeled and tracked vehicles for AAN operations. As noted previously, a starting point for M&S of combat vehicle performance is the NRMM (North Atlantic Treaty Organization Reference Mobility Model). The NRMM describes the following five factors as limits to vehicle mobility.

- *Maneuver-controlled speed* is the limit imposed by man-made or natural obstacles, such as forests or rivers.
- *Force-controlled speed* reflects the inability of a vehicle to move through unfavorable soil conditions or up a steep slope.
- *Visibility-controlled speed* is the limit on speed imposed by the driver's inability to see what is over the next hill or around the next corner.
- *Ride-controlled speed* is the limit on speed imposed by the amount of energy the human body can absorb while moving over rough terrain.
- *Tire-controlled speed* is the speed at which tires begin to disintegrate.

WES has conducted exhaustive tests comparing wheeled and tracked vehicles in terms of these five factors (DA, 1991). As expected, tracked vehicles exhibited a higher maneuver-controlled speed. (The wheeled vehicles that were tested tended to nose down and had insufficient traction to exit linear obstacles, such as ditches.) The tracked vehicles also moved better over unfavorable soil because of their larger area of ground contact. However, tracked vehicles had no advantage in visibility-controlled situations and no inherent advantage in ride-controlled situations. (WES has found that combat vehicle speed in many areas of the world is ride-controlled.) Enabling technologies that could raise the limit of each speed-limiting factor are described below.

Maneuver-Controlled Speed

Some obstacles, such as dense forests and large rivers, cannot be traversed by either wheeled or tracked vehicles. Remote sensing could offer the commander alternative routes to an objective (see the discussion of situational awareness in Chapter 6). Software to speed processing of obstacle information gathered by the sensors is especially important. Active suspension and some type of "ditch-ejector" would assist a wheeled vehicle in breaching minor linear obstacles. A "smart" suspension system would increase both cross-country speed and improve the crossing of small trenches and obstacles.

Force-Controlled Speed

A high ratio of horsepower to weight would help overcome this limit. Remote sensing of soil conditions would be useful for determining the soil conditions of various routes. Guaranteed traction to each wheel can be accomplished with slip control. Articulated powered joints, to permit both the coupling of modular vehicle units and the powered elevation of selected units, would also help overcome this limitation and would enhance the vehicle's ability to cross trenches and small obstacles.

Visibility-Controlled Speed

Visibility-enhancing sensor systems will be key to overcoming this limitation. These sensors could "peer through" (penetrate) smoke, obscurants, and foliage far enough to allow the driver to increase speed. Decision aids, a heads-up display, and elevated optics would also help drivers maintain high ground speeds when normal line-of-sight vision is limited.

Ride-Controlled Speed

The impact energy transmitted to the driver could be limited by active-suspension technology or mechanical isolation of the cab. A radical approach that would eliminate this limitation would be to remove the driver (and crew) from the vehicle; that is, to use uncrewed vehicles. Evidence has shown that drivers can adapt to the severe "jostling" (trilateral acceleration) associated with cross-country driving, but soldiers rarely experience these conditions frequently enough during training to become acclimated because the risk to both the driver and the vehicle is considered unacceptable to most commanders. Vehicle simulation trainers with three-dimensional movement would be useful for training drivers to operate at high-speeds over rugged terrain.

Tire-Controlled Speed

New tire materials and centrally controlled tire inflation capability (assuming the tires are pneumatic) could help overcome this limitation. Control of tire pressure would match the vehicle tires to the soil conditions. Run-flat tires, which will soon be commercially available, would also be useful for wheeled combat vehicles with pneumatic tires. Tire and tread materials that minimize the heat caused by deformation would reduce not only the wear due to thermal deterioration but would also reduce the significant thermal signature of both wheeled and tracked vehicles.

General Comments

The committee compared the advantages and disadvantages of future wheeled vehicles—supported by the enabling technologies described above—with tracked vehicles in terms of meeting AAN performance objectives, as well as in terms of reducing logistics burdens. Given the AAN objectives, the committee concluded that the Army should focus on advanced wheeled vehicles for the AAN. Of course, trade-off analyses will be necessary to confirm this preliminary conclusion. The trade-off analyses should quantify the relative advantages of various wheeled and tracked vehicle configurations using the distributed M&S environment.

A suitable family of vehicles for the AAN would incorporate lightweight, high-performance materials, possibly organic-matrix or metal-matrix composites, nonconventional metal alloys, or intermetallics (see Chapter 4 and Appendixes C and D). These vehicles would consume less fuel and require fewer spare parts and maintenance support than current vehicles. Most important, the AAN commander would have a mobile force that could traverse moderate terrain at more than 130 kilometers per hour (80 miles per hour). ("Moderate terrain" excludes both impassable areas, such as the Swiss Alps, and favorable areas, such as the Saudi Arabian desert; in the latter, higher speeds may be possible.) The vehicles would have a rich array of sensors to ensure situational awareness and could be operated with a minimal or even no crew.

However, the 15-ton vehicles in this family will have much less protective armor than current battle tanks. They may be equipped with a variety of active protection devices in addition to armor (see Appendix D). To survive the most lethal enemy fire, they would depend mostly on avoiding being hit through situational awareness, agility, and stealth.

The committee, unlike many individuals in the Army, is not convinced that the power plant for future vehicles ought to be either electric or hybrid-electric. As the committee noted in Chapter 4, the duty cycles typical of suggested AAN operational concepts might not give hybrid vehicles an advantage in fuel economy over straight mechanical drives. Careful exploration of the likely duty cycles for typical AAN missions, as part of rigorous design trade-off analyses that include other considerations, such as electric power for armaments and other subsystems, will be necessary to determine the optimal power plant and drive configuration (see Appendix E).

The main armament of the lead combat vehicle may not be a gun capable of kinetic energy penetration of heavy armor. A quantified study of trade-offs may favor other platforms or systems to defeat heavy armor (see Chapter 6). The committee believes that M&S is the only way the Army can evaluate and assess competing requirements for AAN combat vehicle designs.

Remote Sensing to Enhance Battlefield Ground Mobility

A continuing concern of the Army mobility community has been that detailed, accurate terrain data for cross-country movement might not be available from preoperation mapping. An initiative under way by the National Imagery and Mapping Agency is to map more than 80 percent of the world's surface (the missing areas will be in the polar regions). However, the data will have a vertical resolution of only 30 meters, which is not adequate for planning cross-country movement. Although the sensor technology, when used with a conventional aircraft as the platform, can acquire data at a 10-meter resolution, translating the data into a usable digital product at maximum resolution requires enormous computational capabilities; each hour of data acquisition would require 50 hours of processing time.

The U.S. Army Corps of Engineers' objective for supporting military operations is to provide a digitized elevation map for a 90-km^2 area to a vertical resolution of one meter within 72 hours, from the start of data acquisition by an aircraft (possibly a UAV) until the digital product is delivered to the operational commander. Although this capability would provide a terrain baseline, many things can change in a combat area in 72 hours. The enemy could blow up a bridge. Rain could make a route impassable. The destruction of a dam could flood an area. Enemy sappers could construct an impassable abatis.

In addition to baseline data, a commander planning or executing a maneuver from point A to point B would benefit from real-time updates of changes in the terrain (i.e., physical and cultural geography). The sensor system, perhaps linked to the global positioning system for accuracy, would report changes to the terrain database in the area of potential maneuver routes for all operations. Developing this capability would require the resources and cooperation of WES, TARDEC, the Corps of Engineers Topographic Laboratory, and perhaps others.

Reducing the Size of Vehicle Crews

Reducing the crew size in a fighting vehicle can reduce the vehicle weight considerably because the enclosed volume can be reduced, requiring less material, particularly less armor. Reducing the size of the vehicle can also aid in stealth and agility trade-offs with the weight of passive armor (Appendix D). The ultimate in crew reduction is an unmanned (robot) vehicle.

Besides the 15-ton crewed fighting vehicle, the Army has considered 7-ton crewed and uncrewed vehicles. If progress is made in research and development, even smaller unmanned ground vehicles (UGVs) designed for special combat purposes may be feasible. Specialized UGVs might range in weight from a ton down to just a few kilograms.

The various military services are developing UAVs (unmanned aerial vehicles) and unmanned undersea vehicles (UUVs), in addition to UGVs. At present, the principal drivers for these programs are operational and performance objectives rather than logistics. Many factors specific to each vehicle concept and its intended use in the force affect whether an unmanned vehicle will increase or decrease logistics support requirements.

Smaller UAVs and UGVs could be used as sophisticated mobile sensor systems, "smart weapons," or soldier-safety alternatives (e.g., for clearing mines and reconnaissance), rather than as potential substitutes for crewed vehicles (or dismounted soldiers), and they may add to the logistics burdens. If an unmanned vehicle partially or completely replaces a crewed vehicle, a key consideration is the extent to which the unmanned vehicle (or several of them) reduces the number of manned vehicles necessary for a given operational capability. Logistics support requirements will also depend on whether an unmanned vehicle is tele-operated, semi-autonomous, or fully autonomous. Rational decisions about these complex trade-offs require at least unit-level engagement analyses based on detailed system/subsystem engineering models (see Chapter 3).

The use of robotics science and technology to provide *automated vehicle subsystems-enabling* reductions in crew size for manned systems—seems a promising way to reduce vehicle weight and volume. Furthermore, this incremental approach to removing the human soldier from fighting platforms seems more realistic than unmanned vehicles for reducing logistics burdens in the AAN time frame.

Over time, the general approach of subsystem automation could be extended to the automation of some of the vehicles in a platoon of vehicles (or analogous tactical unit that maneuvers and fights in close coordination), with human platoon commanders or other crew in one or more of the vehicles. In effect, the platoon would become a "minimally crewed system," with some vehicles acting as automated subsystems. This "semi-automated platoon" approach to vehicle automation would provide invaluable experience and a test bed for technologies that could eventually (well after 2025) lead to fully autonomous fighting vehicles with the flexibility and effectiveness of today's mounted soldiers.

UGV Mobility

The five NRMM (NATO Reference Mobility Model) factors that affect the cross-country mobility of crewed vehicles can also be applied to UGVs:

- *Maneuver-Controlled Speed.* If UGVs are smaller than crewed vehicles with similar functionality, they may be more capable of traversing some terrains, such as narrow trails. There will always be some obstacles that a ground vehicle cannot overcome, whether or not a human is aboard.
- *Force-Controlled Speed.* Because a UGV does not need a crew cabin, the engine can be larger for the same total system weight, yielding a higher ratio of horsepower to weight. Increasing this ratio is useful for attaining high force-controlled speeds.
- *Visibility-Controlled Speed.* The observer-operator of a tele-operated UGV could have a wider range of vision than the driver of a crewed vehicle. The development of sensor systems to improve access to terrain data for drivers of crewed systems will also contribute to UGV development.
- *Ride-Controlled Speed.* UGVs may have the greatest advantage over crewed vehicles in this area. The ride-controlled speed limit for a UGV is the speed at which mechanical shock and vibration will damage the vehicle's mechanical or electronic assemblies. For a given terrain, this speed may be much greater than the speed at which a human occupant can avoid injury and retain operational control of a vehicle.
- *Tire-Controlled Speed.* Unless the tires are lighter or of a different type, UGVs would have no direct advantage over crewed vehicles in this area.

Robot Vehicles

A large number of robot vehicles are either in production or under development worldwide. As Table 5-2 shows, most of them are in the United States, where more than 50 percent of the manufacturers and developers for all of the vehicles in the table are located (UVH, 1997). In terms of the concepts under development and expenditures, most of them are UAVs. However, even after 20 years and $3 billion dollars, the development of UAVs has not been a complete success. Some of the problems are with the aircraft itself, but the major difficulties involve nonaeronautical problems, such as communications, control, electromagnetic interference, and video transmission (Crock, 1997).

Although much of the UAV activity has been led by the Air Force and Navy, the Army also had a program for a high-altitude UAV called "Hunter" (terminated in 1998) and has been given the responsibility of testing a tactical UAV, the Outrider, for low altitude operation. These UAVs, as well as the rest of the U.S. military developmental program, are platforms for sensors and the communication of intelligence, not weapons platforms. At the research level, however, both the Navy and Air Force have expressed interest in potential weapons-bearing air vehicles (uncrewed combat air vehicles).

Table 5-2 also shows that UGVs have not received as much emphasis as UAVs and UUVs. Only 17 percent of the worldwide programs by number are for ground vehicles, and only one is currently in development in the United States. Research on UGVs, which the committee considers to be prime candidates as special-purpose vehicles in AAN applications, *has lagged far behind the research on UAVs.* The reason for the lag may be that the mobility control environment for traversing terrain is more complex than the relatively homogenous control environments for flight through air or travel under water. In addition to communications and control challenges similar to but greater than those faced by UAVs and UUVs, UGVs must traverse varied soils and terrain. Determining and executing a path, negotiating or avoiding obstacles (natural and man-made), and maintaining or recovering functional traction (avoiding upsets) are challenges UAVs and UUVs do not face. Ideally, UGVs will operate autonomously, but most existing models are tele-operated; that is, they have partial autonomy but are operated by humans at a distance from the vehicle. Among the various means being investigated to control UGVs in this difficult environment are radio line-of-sight, fiberoptic cable, and hard wires.

The UGVs currently produced in the United States run the gamut from small special-purpose devices used by police departments for explosives detection and surveillance, to vehicles the size of construction backhoes used for ordnance removal, to armored bulldozers or tank-like vehicles used for mine detonation (UVH, 1997). Although these vehicles are listed in Table 5-2 as "in production," in most cases the production volumes are very small.

The Army hopes to benefit from progress in the development of communication and control for UAVs and UUVs and has several memoranda of understanding with other service programs to share in the technological progress on unmanned vehicles. Obviously, Army resources should be invested in Army-unique ground mobility requirements for UGVs rather than in duplicating the efforts of other programs on unmanned vehicles.

TABLE 5-2 Unmanned Vehicles Worldwide

Country	UAV (Air)		UGV (Ground)		UUV (Underwater)		Total
	Production	Development	Production	Development	Production	Development	
United States	21	24	13	1	23	2	84
United Kingdom	2	5	4	6	7	0	24
France	5	2	2	1	2	0	12
Germany	2	2	0	0	1	1	6
Israel	4	3	0	0	0	0	7
Italy	3	0	0	0	1	0	4
Canada	2	1	2	1	0	0	6
Ireland	0	0	3	0	0	0	3
Turkey	0	1	0	0	0	0	1
Russia	1	0	0	0	0	0	1
Czechoslovakia	1	0	0	0	0	0	1
Japan	1	1	0	0	0	0	2
Sweden	0	2	0	0	0	0	2
South Africa	1	2	0	0	0	0	3
Switzerland	1	0	0	0	0	0	1
Spain	0	1	0	0	0	0	1
TOTAL	44	44	24	9	34	3	158

Source: Committee data compiled from (UVH, 1997)

Current UGV Applications

When the committee reviewed the Army-unique technological requirements for robot vehicles, it became apparent that the present Army program is part of the consolidated effort under the Joint Robotics Program (JRP) directed by the Office of the Secretary of Defense. The JRP program includes a number of components whose names indicate their objectives: Vehicle Teleoperation Capability, Tactical Unmanned Vehicle, Robotic Ordnance Clearance System, Basic Unexploded Ordnance Gathering System, UGV Technology Enhancement and Exploitation (UGVTEE) Program, and the Joint Architecture for Unmanned Ground Vehicles (DoD, 1997d).

The focus of the UGVTEE program is on exploiting research by other DoD and government agencies, as well as industry and academia that meets current Army needs. UGVTEE includes field experiments to help develop the optimal interaction between soldier users and robot-vehicle technologists. A successful robotics program requires, first, that the robot vehicles have the mechanical and technical capabilities to execute the missions assigned to them. Second, the soldier users must know how to make the best use of those capabilities. Third, users must become acclimated to (i.e., "comfortable") working with a mechanical adjunct.

A series of UGVTEE field exercises, under the headings of Demo I and Demo II, are using tele-operated and supervised high mobility multipurpose wheeled vehicles (HMMWVs) to test and evaluate the relationships between users and machines (DoD, 1997d; DoD, 1997c). The committee believes these exercises should be continued as more advanced robotics and control technologies for automated vehicle systems are developed. The next step will be Demo III, sponsored by DARPA and intended both to increase the capabilities of supervised and semi-autonomous vehicles and to develop the user-vehicle interface.

The committee recommends that the Army continue lending its full support for UGV demonstrations and development. Demo III will be necessary to the Army's continuing effort to understand and exploit UGVs. The Army programs in UGVs are conducted by the ARL, TACOM, with support from the WES, and the Army Aviation and Missile Command. Demonstrations of UGVs for the Army are coordinated by the Joint Program Office, Unmanned Ground Vehicles and Systems, which is located at Redstone Arsenal in Huntsville, Alabama, and is similar in organization and function to the Joint Program Office for UAVs.

Future Applications for UGVs and Required Technologies

A variety of programs have been proposed for UGVs, ranging from somewhat simplistic tethered vehicles to tele-operated units and semi-autonomous and fully autonomous vehicles. These concepts range in size from full-scale vehicles to matchbox-sized surveillance devices. A summary of proposed applications, compiled by the Institute for Defense Analyses, is listed below (IDA, 1996b).

- security, such as interior and exterior security of facilities, rear area security, and convoy security
- robot engineer vehicles to perform specialized functions, such as breaching obstacles and mine fields; digging emplacements and fortifications; detecting, recovering, and detonating mines; and crossing gaps

- combat support functions, such as decoy and deception, laying wire or cable, evacuating casualties, and eliminating obstacles
- robot trucks and other logistic vehicles for resupplying, rearming, and refueling other vehicles
- RSTA (reconnaissance, surveillance, and target acquisition) vehicles for robot scouts, special forces vehicles, and reconnaissance for nuclear, biological, and chemical warfare agents
- specialized vehicles for urban operations
- robot vehicles as direct-fire platforms, howitzers, air defense weapons, nonlethal weapons carriers, or countersniper vehicles

Advanced capabilities required to support autonomous vehicles will vary, depending on the tasks the vehicle is required to perform. For autonomous vehicles to serve as RSTA vehicles or as direct-fire platforms, they will have to have the following capabilities:

- secure communications and control
- data compression
- enhanced displays for remote vehicle control
- autonomous path following and obstacle avoidance
- automatic target tracking
- precise real-time location and identification of friendly and enemy units and equipment, including onboard identification of friend or foe (IFF)
- precision targeting and target servicing
- automatic registration of killed targets

By 2025, fully automated, autonomous systems should be capable of emulating various functions of a crewed vehicle or dismounted soldier, but they will still lack abstract decision-making capabilities and other "thought-like" capabilities that involve creativity and ingenuity. These robots will range in size from less than a cubic centimeter to full-sized air and ground vehicles. Autonomous vehicles will be capable of engaging in combat missions involving reconnaissance or mine detection and clearance, as well as serving as weapons platforms for direct and indirect fire. Autonomous vehicles may also deliver supplies and ammunition to ground troops, carry bulk supplies to ports of embarkation, and perform other combat support tasks.

Some of the logistics issues related to automated subsystems in a vehicle, as well as to fully autonomous vehicles, are obvious. Compared to a soldier, automated subsystems do not eat or drink, do not need medical care, do not sleep, do not need billeting, and can be squeezed into small volumes. Nevertheless, the logistics support to maintain fully autonomous systems could be considerable, including mechanical maintenance, computer software, and mission planning requirements, in addition to fuel and energy requirements. Less obvious advantages, but the primary logistics advantage for AAN planning, are potential reductions in weight that could be achieved by incorporating robotic technologies into future combat vehicle designs to reduce crew size and to increase combat effectiveness, which could ultimately reduce the number of vehicles needed for the battle force.

The committee does not foresee a completely autonomous AAN battle force. One Army officer told the committee that he could foresee a robot wingman for his tank, but he was convinced that there had to be at least one manned vehicle for effective combat (Brendel, 1997). If automated vehicles are used in the AAN, the committee believes that a combined force of autonomous and semi-autonomous vehicles, rather than a fleet of fully automated vehicles, will best meet AAN mission requirements.

The committee suggests that the Army reevaluate the modes of combat in 2025, when the purpose of "combat" vehicles will not be limited (as current tanks are now limited) to "shock," intimidation, and engaging enemy combat vehicles. Designing a single combat vehicle that can play multiple roles will diminish its overall effectiveness. A family of vehicles with common logistics support characteristics, designed to perform complementary functions that increase the survivability of the entire force, would probably be more effective. The evolution of weapons platforms in both the Air Force and Navy demonstrates that direct "eyeball to eyeball" engagement with an enemy in the air or on the sea is not practical (Wilson, 1996). The Army should consider whether direct engagements by future ground combat systems will be practical.

DISTRIBUTED MODELING AND SIMULATION ENVIRONMENT FOR VEHICLE DESIGN

Status of Current Modeling and Simulation Tools

The NRMM resulted from a significant development program, carried out primarily by WES and TACOM in the late 1960s and continuing through the 1970s, to develop the M&S capabilities required for vehicle system mobility (DoD, 1974). It is based on speed and tractability parameters that characterize a vehicle's mobility. Once specific values for these parameters have been established (or assumed) and a terrain database characterizing the field of operation is available, the NRMM can predict the time required to move from position A to position B in a tactical environment. Routing algorithms in the model select the path of shortest time, avoiding areas of low speed or poor traction. However, the mobility criteria in the NRMM are based on empirical characterizations of vehicle performance, which are significantly influenced by the characteristics of *past and present* vehicles. Although the NRMM's basic predictive capability for ground vehicles will require some improvements, it represents an asset that could be used effectively and built upon to assess AAN vehicle design and mobility requirements.

The NRMM has no capability to model vehicles or mobility concepts that travel off the ground, that is, in the vertical dimension that AAN planners wish to use for in-theater air-mobile operations. In addition, current NRMM implementation, together with supporting M&S tools for engineering analysis of vehicle performance, has significant limitations in the simulation of key elements of vehicle performance (see Box 5-2).

For instance, the VEHDYN (vehicle dynamics subsystem) in the NRMM represents only one-dimensional mobility, straight-line motion on the ground. The NRMM has no capability to represent the three-dimensional dynamic motion of a vehicle traveling at high-speed over rough terrain, so it cannot simulate the effects of active suspension or traction control, hybrid-electric propulsion systems, and related new technologies that will have to be assessed to find the best design for achieving the revolutionary mobility objectives of the AAN.

BOX 5-2 Limitations in M&S Tools for Engineering Analysis of Ground Vehicle Concepts

Engineering models do not accurately predict speed, traction, and fuel consumption.

Model parameters do not account for vehicles with:

- active suspension
- all-wheel traction control
- electric drives (including hybrid electric)
- power sources other than internal combustion engines

Tractional force models based on soil mechanics are not adequate for AAN speeds.

Existing vehicle modeling tools cannot be used to assess the performance or logistics benefits of advanced subsystems and related mobility-enhancing technologies that might enable a vehicle to operate cross-country at high-speed. Nor can they predict fuel consumption or plan routes for advanced technology systems, based on realistic simulations of duty-cycles and corresponding engine power demands (see Appendix E for an example of this kind of analysis for a civilian vehicle). Engineering models that can accurately predict speed, traction, and fuel consumption for vehicles with active suspension, all-wheel traction control, electric drive, power sources other than internal combustion engines, and a host of other advanced technologies that may be required to achieve AAN off-road mobility objectives have yet to be developed. Tractional force models that represent fundamental physical interactions between the traction surface and a soil or similar soft surface are not yet adequate to model high-speed cross-country travel.

Accurate simulations of differences in fuel consumption or traction of various system designs under varying operational scenarios (duty cycles), will require models that include realistic representations of the physical processes that determine these important system-level performance characteristics. Without these "first-principles" models, trade-off analyses for alternative designs will be inadequate—unless physical prototypes of the alternative systems are constructed and tested to obtain validated initializing data for the heuristic relationships used by simpler models. Unfortunately, the committee found no evidence that the Army has begun to develop, or has plans to develop, models at the vehicle-system or mobility-subsystem level that would incorporate sufficient "first-principles" modeling to simulate traction and fuel consumption for ground vehicle concepts that are still in the design stage (before prototyping). First-principles modeling capability is a prerequisite for the distributed hierarchical M&S environment to become a reliable tool for making rational trade-offs among vehicle characteristics, tactical alternatives, and force structures in terms of logistics burdens and revolutionary mobility.

Advances have been made in characterizing soil surface conditions as a function of weather, but accommodating terrain data from remote sensors will require further refinements. Recent developments reported by WES in predicting soil or terrain characteristics based on historical weather information appear to be promising, but they must be linked with (1) advanced information systems for situational awareness and (2) mobility M&S tools for system performance and analyses of logistics trade-offs.

Technology Extensions

Considering the myriad tactical and materiel alternatives that must be integrated to create an effective, logistically supportable AAN battle force, better M&S tools will be critical to making rational trade-offs in the time available. Systematic development of highly mobile systems will require advances in M&S technology in three areas: (1) off-road mobility analysis, (2) mission rehearsal analysis, and (3) driver training for high mobility. Each of these areas is discussed below.

Off-Road Mobility Analysis

M&S capabilities to support off-road vehicle mobility have not kept pace with technological advances in vehicle subsystems or with AAN mobility requirements. A broad base of M&S tools will have to be developed (Box 5-3) to meet AAN vehicle system performance and logistics objectives. Significant advances are required in the technology for modeling off-road traction, surface and air propulsion, and related mobility factors. The Army can take advantage of basic developments in vehicle dynamics, M&S software, hardware-and-driver-in-the-loop vehicle driving simulators, and DIS (distributed interactive simulation) of vehicle concepts. The obsolete VEHDYM subsystem of NRMM should be replaced with the simulation software already being used by TARDEC and commercial vehicle manufacturers.

Predicting the traction of highly mobile vehicles on soft soils, including the effects of traffic on soil, will require significant improvements in modeling. Both theoretical and empirical models of the interactions between tires or tracks and soil will be necessary. These models must give reasonably accurate predictions of tractional and lateral forces as a function of spindle position, velocity, and tire or track speed. Extending the current modeling capability will enable the Army to evaluate the benefits of advanced technology subsystems, such as active suspension and traction control, electric drives, and articulated vehicles. With this capability, the Army would have the data necessary for making tactical mobility assessments using the NRMM.

Synthetic environment modeling of soil characteristics, terrain geometry, and cultural features affecting both ground and air mobility will have to be substantially improved for AAN system analyses. Soil characteristics, both surface and subsurface, which are critical to mobility modeling, must be incorporated into databases that can be populated with data obtained through field tests or in-theater measurements. Terrain geometry and databases should be fully three-dimensional, including the characteristics of obstacle types, such as rocks, logs, and other geometric features that affect mobility. Cultural features, such as brush, small trees, and human-built obstacles, that can influence both ground and air mobility should also be incorporated.

Empirically based mobility models contained in the NRMM will have to be updated to take advantage of improved capabilities for simulating vehicle dynamics. Knowledge bases and expert systems technology could be incorporated to help the Army assess AAN mobility alternatives. Mobility characteristics associated with active suspension and traction control, local sensing of terrain data, and other advanced technologies for vehicle subsystems must be incorporated into the NRMM tactical mobility representation. These and other extensions to the existing NRMM will be essential for assessing the trade-offs among a wide range of concepts and technologies for AAN vehicles and advanced mobility.

BOX 5-3 Mobility M&S Technology Developments

Tractional models for high-speed vehicles on soft soils

- effects of prior traffic on soil
- tire/track soil interaction

Synthetic AAN environment modeling for distributed interactive simulation

- soil characteristics
- terrain geometry
- cultural features affecting surface and air mobility

Extended empirically based NRMM mobility models

- dynamic simulation capability

High fidelity, real-time models of AAN vehicle concepts for hardware and soldier-in-the-loop simulation

- traction and vehicle suspension models
- active suspension and traction control models
- hybrid-electric power train models

Air mobility models

- in-theater mobility of an AAN force
- integration into next-generation mobility analysis software

Fuel consumption models that account for

- energy dissipation at interface of tire or track with soil
- interaction with cultural features
- active suspension and traction control
- hybrid-electric power trains
- vehicle speed and maneuvers

Motion-based simulators can test hardware concepts in interactions with human drivers (hardware-and-soldier-in-the-loop simulators). Simulators would provide a rapid and relatively inexpensive way to experiment with AAN vehicle concepts and technologies in a "virtual proving ground." The uncertainties associated with vehicle and driver performance at the high cross-country speeds being considered for AAN could be quantified through simulators.

In summary, the mobility assessment models currently implemented in the NRMM are based on conventional vehicle configurations and are limited to land mobility; they cannot represent all of the technology and subsystem options available for the AAN. The Army will need engineering M&S extensions, and their associated mobility representations in the NRMM, to analyze revolutionary AAN land-based systems. The following high fidelity, real-time modeling capabilities will be required:

- traction and vehicle suspension models
- active suspension and traction control models
- hybrid-electric power train models

- hardware-and-soldier-in-the-loop vehicle concept simulators that can incorporate results from the subsystem models into a virtual proving ground approach for system testing
- DIS models for analyzing the performance of multiple vehicles as a fighting unit, incorporating results from the virtual proving ground

This degree of linking across levels of M&S capability while simulating the real-time behavior of systems and drivers with enough fidelity to yield dependable predictions of the performance characteristics of vehicle systems and tactical units will require advanced computing capabilities. Models and their computer implementation will have to be targeted for the specific class of simulator (e.g., DIS nodes and developmental virtual proving ground simulators).

In addition to these M&S extensions and improved linkages for modeling and simulating ground mobility, *air mobility models* that can represent the in-theater mobility of an AAN force should be developed and integrated into a next-generation mobility analysis software package. These models should focus on the chosen air mobility mechanism (e.g., helicopter, tiltrotor, or fixed-wing aircraft). In addition, if any of the surface-effect vehicles prove to be viable, realistic design and trade-offs among design alternatives will require an entirely different set of terrain data.

The Army will also require fuel consumption models for both air and ground systems. The ground versions of these models should account for energy dissipation at the interface of tire or track with soil, interaction with terrain cultural features, effects of active suspension and traction control technologies, the performance of hybrid-electric power trains, and the effects of vehicle speed and maneuvers. First-principles models of vehicle power train and propulsion subsystems and their interactions with the tactical environment could predict consumption rates as a function of vehicle design and use. Fuel supply is emerging not only as a major AAN logistics burden but also as a critical hurdle to meeting AAN sustainment objectives. Therefore accurate predictions of fuel consumption will be essential to meeting AAN goals.

Mission Rehearsal Analysis

Mission rehearsal analysis could be based on the same M&S capability used for AAN logistics trade-off analysis. During the committee's deliberations, high-fidelity mission rehearsals using mobility M&S tools was identified as an important means of improving logistical efficiencies through better tactical and mission supply planning (Box 5-4). Credible mission rehearsal simulations would enable commanders to estimate the supplies required for a specific AAN mission more accurately. Logistics provisioners could then transport "just enough" materiel into the battle zone, reducing the logistics burdens of transporting more materiel than is needed and having to manage the excess during the operation.

BOX 5-4 M&S Tools for AAN Mission Rehearsal Analysis

- Planning tactics
- Determining supply requirements
- Designing supportable vehicles
- Predicting fuel requirements
- Minimizing mission logistics

Implementations of the NRMM on personal computers, which were demonstrated to the committee at WES, showed that these mobility M&S tools could be the foundation for mission rehearsal analyses. Although significant development and extension of the basic tools will be necessary to represent AAN vehicle systems and tactical operations, most of this work would also be applicable to analyses of performance and logistics trade-offs. The technological challenge will be to create tools that can be used by war fighters and to implement algorithms that can run on inexpensive field computers.

BOX 5-5 Vehicle Motion Simulators

Test drivers are capable of much higher cross-country speeds than soldiers in the same vehicles because:

- soldiers are not permitted to train at speeds that would damage vehicles
- motion cues are essential for training soldiers to achieve high vehicle speeds

High fidelity models for training soldier drivers:

- are developed with trade-off analysis models
- will require computational advances to run in real-time training simulators

Simulators to meet AAN speed objectives:

- will use tests and existing simulators to determine required motion cues.
- should be built for use during design and system trade-off analyses

Driver Training

Moving combat forces at the high-speeds required for AAN operations will require that drivers achieve and maintain speeds as high as 130 km/h across open terrain. Training Army drivers to meet this challenge will require fundamental improvements in driving simulators (Box 5-5).

Committee members discussed the possibilities for training vehicle drivers with test engineers at WES, who noted that experienced professional drivers can achieve much higher cross-country speeds than soldiers who have not been adequately trained. Training simulators that would train soldiers to function effectively at high-speeds would have to have very high fidelity and include the harsh motion cues encountered during high-speed cross-country maneuvers. Systematic testing and evaluation with advanced motion-based simulators could be used to determine the level of fidelity of simulator motion cues in a training simulator for AAN applications. The M&S capabilities required for this functionality would be derivatives of those required for determining vehicle system trade-offs and defining logistics requirements. However, none of these capabilities exist today.

The development of M&S technology for driver training simulators should be integrated with the development of vehicle systems. Driver training simulators would be effective tools for assessing human factors, optimizing training simulations, and assisting in development of vehicle system designs. Training simulators could also be integrated into a DIS environment for operational testing and evaluation. This would require that a training simulator be developed prior to the actual vehicle system.

SCIENCE AND TECHNOLOGY INITIATIVES TO REDUCE MOBILITY LOGISTICS BURDENS

Based on the preceding analysis of the logistics burdens associated with mobility requirements for AAN-style operations and the technological opportunities for reducing these burdens, the committee concluded that the Army should pursue the following areas of research and technology development. The order of the numbered items under a heading reflects a rough order of priority.

Operational Mobility

Air Mobility Alternatives. The committee is not optimistic that the Army's current or planned aircraft programs will provide the operational mobility necessary for AAN missions. The R&D risks in this area are high, and the acquisition costs may be prohibitive. In addition, even if the R&D objectives are realized, the resulting aircraft will add significantly to overall logistics demand for the AAN battle force mission. Nonconventional, novel concepts for air mobility, however, might lead to a revolutionary breakthrough. The WIG concept is one example of an approach that seems to warrant a careful and open-minded evaluation. Although WIG technology has been demonstrated to some extent, both fundamental research on the aerodynamic principles and thorough feasibility studies would be essential before the Army could make a commitment to technology development. A similar combination of foundational research and exploratory testing for feasibility in military operations would apply to other novel air mobility concepts. The search for new approaches to air mobility should be a joint effort; at the same time, the Army must ensure that Army requirements are fully met in the process. (This initiative pertains to reducing logistics demand for the *operational mobility* requirements for the AAN battle force. Obviously, the battle force will also have a continuing need for a limited number of aircraft for combat and support missions the battle area.)

Tactical Ground Mobility

1. Mobility M&S Environment for System Design and Trade-off Analyses. Decisions regarding vehicles will be critical to determining AAN logistics needs. These decisions must be made from a total systems perspective. The choice of fuel, for example, cannot be made without considering the vehicle power plant. The choice of vehicle power plant cannot be made without careful consideration of the vehicle duty cycle. The choice of power plant may also determine the main gun; conversely, the choice of the main gun may influence the choice of power plant.

The development of a family of vehicles that weigh 15 tons or less is not only feasible but also desirable for meeting AAN operational goals. The technologies for an advanced wheeled vehicle can be developed in the near-term because many of them have already been implemented and could be integrated into a total system with relative ease.

Unfortunately, the current vehicle mobility models (the NRMM) are inadequate to assess the performance and logistics benefits of active suspension and traction control, electric drive power trains, or other advanced subsystem technologies. These models cannot simulate cross-country speeds as high as 130 km/h, certainly not 200 km/h. They cannot be used to optimize route planning for both speed and fuel conservation. Therefore, the NRMM is only a starting point for the development of AAN mobility concepts. The Army should support updates and extensions of the NRMM for the kinds of design and trade-off studies discussed in this chapter and in Chapter 3.

Developments in M&S technology that would support off-road mobility analyses are listed below:

- traction models for high-speed vehicles on soft soils that can represent the effects of prior vehicle action on soil and the interaction of tires or tracks with the soil and can incorporate soil characteristics, terrain geometry, and cultural features
- enhanced NRMM with an updated VEHDYN simulation subsystem
- high-fidelity, real-time motion simulators for hardware-and-soldier-in-the-loop simulations that can be used as virtual proving grounds for advanced vehicle technologies and design concepts, as well as for modeling human-vehicle interactions and for driver training
- air mobility models, integrated with next-generation mobility analysis software, to analyze the in-theater mobility of an AAN battle force
- M&S capability for fuel consumption that accounts for energy dissipation at the tire or track interface with soil, for vehicle interaction with cultural terrain features, and for assessing candidate technologies and design concepts for AAN vehicles

2. Technology Development to Support a 15-Ton Wheeled Combat Vehicle. In contrast to the aircraft program, major improvements in ground vehicle mobility are possible and not excessively challenging. The committee considers a number of advanced technologies and design concepts to be well within the realm of near-term development. Use of these technologies would enable the expanded use of wheeled vehicles for AAN, achieve the principal AAN objectives, and enable meaningful logistics trade-offs during system design. The committee recommends that a research and development program be established to demonstrate these capabilities within a five-year period.

TARDEC and WES are currently doing some research in ground mobility; however, the Army has not placed a high priority on developing a wheeled vehicle, and the WES program has suffered from lack of financial support.

3. Look-Ahead Sensor Systems to Increase Vision-Controlled Speed. Sensors for cross-country mobility have enormous potential and little technical risk. A program in this area would require the resources and cooperation of WES, TARDEC, the Corps of Engineers Topographic Laboratory, and perhaps others.

4. Reducing Crew Size through the Evolution of Automated Systems Technologies. Fully autonomous ground vehicles will be important for performing specialized functions, but UGVs will not replace crewed vehicles and will not lessen the logistics burden. In the long-term, as automated subsystems are incorporated into manned systems, UGVs may become a component of platoon-like fighting units, in which fewer vehicles will require human operators. The UGVTEE Demo III programs previously discussed appear to be worth pursuing for the specialized capabilities it could offer an AAN battle force, although logistics burdens may not be immediately reduced.

5. Mission Rehearsal Extensions to Mobility M&S Tools. Mission rehearsal mobility analyses will be essential for tactical planning and for determining logistics support requirements. A mission rehearsal capability based on mobility M&S tools can be helpful for designing supportable vehicles, forecasting fuel requirements for AAN operations, and minimizing mission logistics.

6. Driver Training Extensions to Mobility M&S Tools. The high-fidelity models and simulators required to train drivers without risk to them or their vehicles could be developed along with M&S simulators for mobility trade-off analyses. However, running training simulators in real time will require computational advancements.

6

Engagement

In this chapter the committee examines technology for reducing the logistics burdens associated with combat engagements, including projectile weapon systems (gun tubes and missiles) with an emphasis on precision guided munitions, energetics (propellants, explosives, and warheads), and directed energy systems. Technologies and systems are assessed in terms of their potential for reducing logistics burdens for an AAN battle force.

The principal logistics burdens directly linked with engagement are the weight and volume of ammunition, the weight and volume of the lethal systems transported to, from, and within the area of operations (operational and tactical mobility), and the energy requirements for lethal systems that must be supplied from battlefield fuel. In general, technology could reduce logistics burdens by ensuring that every round of ammunition fired hits its target and is effective ("one round, one hit, one kill") or by decreasing the weight requirement per round. Significant reductions in both of these categories could be achieved through near-perfect situational awareness (SA), precision guidance systems, and highly lethal munitions (or other kill mechanisms). Of these, SA is critical not just to reducing the logistics burdens but also to engaging the enemy successfully.

SITUATIONAL AWARENESS

The DoD defines SA (situational awareness) as "knowledge of one's location, the location of friendly and hostile forces, and external factors such as terrain and weather that may affect one's capability to perform a mission" (GAO, 1998). The importance of SA to success on the battlefields of the next century cannot be overstated. Accurate information about the locations of forces, capabilities, and intentions of both friends and enemies, as well as details about the terrain and weather, have been uppermost in the minds of commanders throughout history. Even before the time of semaphores, scouts and couriers were essential to battlefield sensing and communications. Army XXI forces will have networked computers capable of passing digitized information, including detailed images and processed intelligence, to all levels of the command hierarchy. In the AAN time frame, continuing advances in information technologies should ensure even better SA. Appendix F discusses the range of opportunities for—and the potential pitfalls of—the information processing and telecommunications technologies with the greatest potential impact on AAN logistics.

SA begins with knowledge of friendly and enemy locations, but SA technologies involve more than the global positioning system (GPS). Accurate SA will provide the operational information required to project a battle force of appropriate size, with the right suite of weapons and equipment, at the optimum time and place. Determining the numbers of soldiers, units, vehicles, and systems for a "right-size" force is essential for logisticians to provide "just enough" materiel (i.e., with allowances for risks) and to avoid burdening the force with excessive quantities of ammunition "just in case."

SA has always been an important factor to support weapons systems for both standoff platforms and close engagement. In Army XXI, and even more so in AAN, the reliance on *maneuver* and *precision fire* to achieve technological overmatch will make near-perfect SA a prerequisite for successful engagement. Figure 6-1 is a schematic representation of the system components needed for near-perfect SA. Computation functions at the sensors, at the command and control nodes, and at the response platforms will require detection, identification, and multisource fusion algorithms even more robust than they are today for mission-critical functions. Otherwise, an opponent skilled in camouflage and deception could defeat the SA system and escape detection. The Army's critical dependence on SA technologies increases the likelihood that information warfare techniques, including electronics countermeasures, will be used. The communications links must be exceptionally robust. Large amounts of data will have to be transmitted securely, with guaranteed reception, over a complex and rapidly changing network, in the face of sophisticated attempts at disruption and spoofing.

At present, precision guided, or "smart," munitions are relatively expensive and are reserved primarily for high-value targets. Highly reliable, miniaturized, integrated systems for sensing and guidance control that can be produced inexpensively and in large quantities will be essential for an AAN battle force that relies on precision munitions for all of its indirect-fire close support.

Networks of miniature, inexpensive sensors will provide the wide-area coverage and advanced warning inherent in the concept of near-perfect SA. Examples include sensor networks for detecting and identifying chemical and biological warfare agents and acoustic sensors for detecting vehicle movement, human movement, and voices.

For the terrain guidance discussed in Chapter 5, the SA system will require a combination of (1) previously stored (in each vehicle) "unchanging" data, such as a terrain database, (2) "look ahead" sensor and processor systems on vehicles that can update information on transient and alterable features (e.g., visibility, soil conditions, road and bridge damage, and mine detection), and (3) remote sensing images and wide-area alerts (e.g., moving target indication) from satellites or UAVs. Real-time integration of data from all of these sources into a "here-and-now" presentation will have to be available on every vehicle to realize the AAN vision of open-formation, high-speed, collaboratively self-routing charges of combat vehicles through the killing zone. For shooters on these vehicles to achieve one round, one hit, one kill accuracy against targets that are beyond their line of sight, the in-vehicle presentation system must be linked with targeting and fire control systems.

The SA system for *logistics command and control* will also depend on sensors, data processing, information integration, and decision-support aids. Technologies applicable to SA in the AAN battle space will have the capability to reduce logistics inefficiencies by minimizing the number of "just-in-case" support requirements. But the full range of opportunities will be realized only if the Army continues to exploit rapid advances in the underlying technologies, rather than assuming that SA has been optimized by a revolution in military logistics when *Joint Vision 2010* has been realized (DoD, 1996).

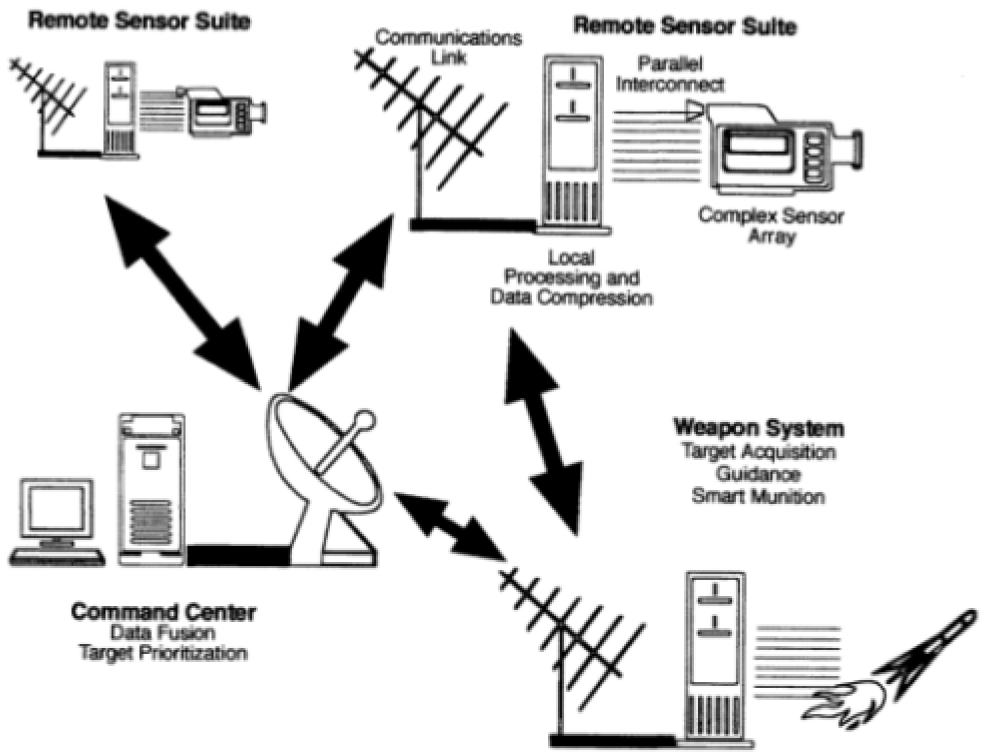

Figure 6-1
Schematic representation of the situational awareness system.

During the study, committee members became concerned that AAN planners and proponents were sometimes complacent about keeping abreast of rapid changes in SA technologies. Even if Army XXI (the Army of the 2010 time frame) has "mental agility" compared with opponents *of that era,* this technological superiority could erode rapidly as the technologies continue to advance. Even if the Army has an unprecedented level of SA by 2010, it must be prepared to maintain its advantage to 2025 (and beyond).

Appendix F highlights some of the technical reasons the committee believes that maintaining superiority in SA will be a demanding task. First, simply maintaining and upgrading the interconnecting hardware and software systems will be a daunting challenge for the Army, as it is for commercial organizations that have only a fraction of the Army's workforce and installed technology base. Second, much of the enabling information processing technology (i.e., "computers") will continue to be driven by commercial markets, rather than by military specifications or DoD requirements. However, the Army cannot assume that commercial markets will solve all of its difficult problems (e.g., fielding components that are reliable and rugged under conditions anywhere in the world).

Third, the rate of advance of any specific SA technology over several decades will be unpredictable. Therefore, the Army can neither rely on a continuation of trends, even if they are well established, nor assume that a physical limit will inevitably halt advances in SA capabilities for which that technology seems to be essential. An example (described in Appendix F) is the current debate in the semiconductor and microprocessor technical community about the applicability of Moore's Law[1] to 2010 and beyond. The bottom line is that the Army cannot assume that trends in advancing the fundamental technologies for SA will remain constant until the AAN era. If and when technology trajectories change, the Army must be prepared to adjust its planning assumptions for maintaining SA dominance and must then follow through with the efficient execution of a timely strategy. If a trajectory shift occurs, an opponent with less advanced technologies may no longer have to modernize a large installed base. This change could give an otherwise overmatched opponent a *technological agility* that could undermine the near-perfect SA on which an AAN battle force will depend.

Rapid innovations in all SA-relevant technologies—including those for basic computing and information processing capabilities-will continue well beyond the time frame for incorporating today's technology into Army XXI. Opponents with later, and therefore better, technology must not outpace AAN forces. SA capabilities must be continually upgraded beyond Army XXI, within resource constraints, without compromising system integrity. The committee believes continuing modernization will be a daunting challenge, especially because new SA systems will be required to meet as yet unidentified AAN engagement system requirements.

PROJECTILE WEAPON SYSTEMS

Technologies for projectile weapon systems can reduce logistics burdens by helping to achieve "one round, one hit, one kill" and by decreasing the total weight transported per round fired. Total weight transported includes the weight of the lethal system and supporting elements (including troops), as well as the weight of the round. This section examines prospective technologies for gun systems, small missile systems for precision attack, precision guided munitions, and energetics, primarily in terms of their potential for reducing logistics burdens of ammunition and fuel. In several instances, the committee uses current system concepts to illustrate the significant factors that can increase or decrease logistics demands and that will be needed in AAN battle force engagement systems.

Gun Systems

Alternative gun propulsion technologies with significant implications for logistics burdens include the electrothermal chemical (ETC) gun, the electromagnetic (EM) gun, and liquid propellants for conventional gun systems. All three have advantages and disadvantages in terms of reducing logistics burdens.

[1] Moore's Law is an empirical generalization first stated in 1965 by Gordon Moore, then the chairman of Intel Corporation. Moore observed that a graph of the growth of memory chip capacity (measured in numbers of transistors per chip or millions of instructions executed per second) approximated an exponential growth curve with a doubling time of one year.

Electrothermal Chemical Gun

One way to increase the range of solid propellant, cartridge-based rounds is to add energy to the propellant combustion via an electrically generated plasma. This is the basis for the ETC gun currently under development by the Army. By implementing the ETC concept, muzzle velocity can be increased using the same amount of gun propellant as in current rounds. This should enable the design of smaller guns and ammunition in the future. The drawback to the ETC gun is the high power required to generate the plasma.

The potential logistics implications of the ETC gun are that the same performance as current rounds could be achieved with smaller, lighter rounds, or rounds of the same weight would need less solid-propellant energy and would thus be less sensitive to hazards. Alternatively, rounds of current weight could have more than a 10 percent increase in muzzle velocity, a greater range, and a higher probability of kill by incorporating projectile guidance sensors and controls. Among the disadvantages to be considered are the added weight of the external power source and the fuel needed to re-energize it.

Army demonstrations of the ETC gun concept have proved that it can augment the chemical energy from gun propellants. The Army objective for this concept is 18 MJ muzzle energy (i.e., combined chemical and plasma energy) and 1.9 km/s muzzle velocity. The basic design of the plasma generator has been completed and could be added to new shells with minimal changes in production processes.

A principal barrier to implementation is that energy storage devices, which must be compact but have the high power density required to develop the 0.5 to 5 MJ plasma energy, have not been developed. Other major hurdles are the sensitivity of the plasma generator to rough handling and the lack of solid-state switches that can handle high power densities.

Electromagnetic Gun (Rail Gun)

A propulsion technology with the potential for greatly increasing the muzzle velocity of projectiles is the EM (electromagnetic) gun, also known as the rail gun. The projectile is accelerated by the strong magnetic field generated when a large electrical current passes through the projectile as it crosses between two conducting rails running the length of the gun tube. Because EM gun technology has the muzzle velocities needed to fire kinetic energy projectiles capable of penetrating the best passive armor (velocities of 2.4 km/s and higher), it is often promoted as the antiarmor armament for a combat vehicle capable of direct-fire "duels" in tank-on-tank engagements. The high muzzle velocity attainable even for large rounds also makes it suitable as a long-range, indirect-fire weapon, *particularly if the round carries a guidance system for homing in on the target.*

A 1987 study by the Army Science Board found that that EM technology might save on weight and volume because fuel to make electricity would replace the propellant charge (not the warhead). Fuel consumption would increase somewhat, but the decrease in ammunition logistics would be significant (ASB, 1987). The *STAR 21 Lethal Systems* report included the following information about high velocity, kinetic energy penetrator (KEP) technology:

> Two factors are fundamental to defeating armored vehicles: (1) penetration and (2) target damage. Penetration of advanced armors, such as ceramics, can be enhanced by increasing the penetrator velocity to above 1.7 km/s. This velocity is close to the upper limit of high performance conventional guns. There are also practical limits to the mass that can be propelled by conventional guns. But the EM launch technology offers the prospect of a substantial increase in both factors. Although armor design can continue to be improved, the possibilities are limited inherently on the defensive side by the weight of armor that can be tolerated in a vehicle. Further, it is very difficult to divert or intercept a KE projectile.
> (NRC, 1993c, p. 2)

The *STAR 21* main report included the following statement on the potential of the EM gun for long-range heavy artillery:

> One potential [long-range heavy artillery] systems concept would combine hypervelocity propulsion, to achieve range, with on board terminal guidance for accuracy. Although hypervelocity projectiles are often discussed for direct-fire antiarmor applications. . . , the first fielded systems to use high-velocity electric propulsion (whether electrothermal or electromagnetic) could well be long-range artillery. . . . If the range of existing artillery could be effectively doubled, with accuracy maintained or even increased through terminal guidance, the firepower resulting from this technology would be of immense military significance.
> (NRC, 1992, p. 85)

The Army-sponsored Institute for Advanced Technology (IAT) and the Center for Electromechanics at the University of Texas at Austin have been working on EM gun technology since 1979 in coordination with the ARL, the Army Armaments Research, Development, and Engineering Center, DARPA, and the U.S. Marine Corps (University of Texas, 1998). Muzzle kinetic energies of 9 MJ and muzzle velocities up to 6 km/s have been routinely achieved in the laboratory. IAT has now installed the first fully self-contained rail gun at Yuma Proving Ground, Arizona, for field tests. The Materials Research Laboratory, Ascot Vale, Australia, is also working on an EM gun.

EM gun technology is not subject to the same limitations on increasing the kinetic energy of a projectile that apply to conventional chemical propellants. Constraints on projectile velocity begin to appear only at much higher muzzle velocities. Cowan (1992) reports a 6 km/s velocity limit for high-performance EM guns because of a limit on increasing momentum as the current increases. Aerothermal heating of an EM projectile requires that the projectile have heat shielding above 2 km/s. At higher velocities, an increasing amount of the muzzle velocity is quickly lost to aerodynamic resistance (NRC, 1993c). The strength of the projectile materials may also become a limiting factor. However, KEPs with velocities of around 4 km/s can defeat all known armors.

One logistical advantage of the EM gun is the smaller weight and volume of the round compared to a chemically propelled round with the same projectile mass (see Figure 6-2). A second advantage is that the round is less sensitive to inadvertent reactions because it contains no energetic materials for propulsion. Third, because of their higher projectile velocity, rounds fired from EM guns have a significantly higher probability of kill, given a hit, than chemically propelled rounds.

A tactical limitation of EM guns as vehicle armaments is that they are line-of-sight weapons until the aim point can be corrected while the projectile is in flight. This limitation means that a vehicle-mounted EM gun for antiarmor assault is basically a frontal or side-attack weapon—although the most vulnerable part of most armored vehicles is the top.

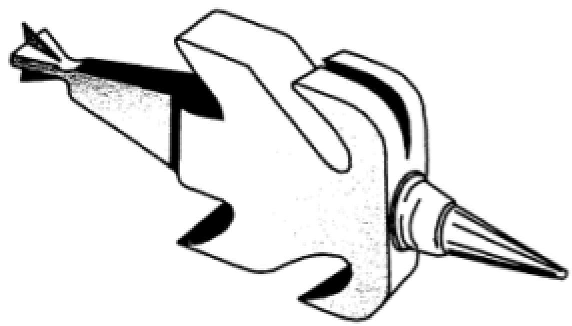

Figure 6-2
Rail gun projectile.

The major logistical disadvantage of EM gun systems is that they require a substantial source of battlefield electric power. They also require fast, solid-state switches that can rapidly switch very high current loads, which must still be developed. The committee was briefed on a concept for a vehicle-mounted 105-mm EM gun. The gun system, comprising the gun and autoloader, 42 rounds of ammunition, and the power management system for the gun, was projected to weigh 10.3 tons. The power management system included a 202-MJ pulsed power source (a compensated pulsed alternator, called a "compulsator"), a 100-MJ lithium-ion battery for intermediate storage, thermal management and high-power subsystems, and 50 gallons of fuel for the compulsator (Johnson, 1997; Halle, 1997). An Army integrated idea team also envisioned a 120mm EM grenade launcher (Freeman, 1997). The spoiler in these concepts is that weight, packaging, and high power requirements severely limit the feasibility of EM armaments.

From the standpoint of logistics burdens, the EM gun system is too heavy to serve as an antiarmor armament for an AAN armored combat vehicle. A concept briefed to a member of the committee was a 40-ton vehicle with a 120-mm gun capable of muzzle velocities greater than 2.1 km/s. A more likely application of EM gun technology to the AAN battlefield would be as a long-range artillery weapon, which could support battle force operations from as far away as 500 km, perhaps from the staging area. Fuel supply logistics would be substantially simplified, and the principal technological obstacle would be a terminal guidance system to ensure long-range accuracy.

A "corps artillery" system concept briefed to the committee would use essentially the same 120-mm EM gun as the combat vehicle concept, but with the compulsator on a separate vehicle platform. While this concept could be used for long-range support, 20 tons per vehicle is probably still too heavy to meet AAN battle force operational mobility constraints.

Liquid Propellant Gun

All of the services, including the Army, have explored the use of a liquid gun propellant. One advantage would be the potential for much lower sensitivity to accidental ignition, which could reduce the weight and volume of protective packaging used with current rounds. Another potential logistical advantage over cartridge-loaded solid propellants is that, in principle, one liquid propellant, transported and stored in bulk, could be used for all calibers of guns except small arms.

However, there are unresolved storage and chemical issues related to ignition. For example, using liquid propellants in large quantities on the battlefield would require new methods of storing, pumping, and replenishing the propellant at each gun tube, much like distributing fuel to vehicles. A separate supply vehicle would only add to the logistics support requirement.

Although the chemistry of liquid propellants has been studied for more than 40 years, the technology is not yet mature. There are major problems, which are still not well understood, with both chemical decomposition and run-away kinetics when the propellant is in contact with transition metals. Variability in propulsive performance is thought to be a function of gun breech temperature. Pressure transients and oscillations continue to be a problem, and the observed transients have not yet been successfully modeled.

Significant logistics advantages would result if the ETC gun concept could be combined with liquid propellant technology. If liquid propellant technology succeeds, the shell casing could be eliminated, allowing the entire breech to be filled with propellant. ETC enhancement of muzzle velocity would compound the increase in projective force for a given breech volume (i.e., gun tube diameter). Thus, the combination of these technologies has the potential for a synergistic combination of much greater muzzle velocity for a given caliber of gun and weight of propellant (decreased weight per round and decreased system weight), together with lower sensitivity of the munition to unintended detonation (which reduces weight and volume of packaging). Because of these potential benefits, the Army should undertake a study to see if combining the ETC gun concept with liquid propellants would lead to a technological breakthrough.

Small Missile Systems for Precision Attack

Small rocket, or jet propelled, missiles are both a battlefield complement to gun-fired projectiles and a potential replacement for them in meeting some AAN lethality requirements. This discussion focuses on potential substitutions as alternative means of reducing logistics burdens for AAN missions. However, the committee expects that the larger Army of 2025 (AAN forces plus Army XXI forces) will continue to use a number of complementary systems, both gun tubes and small missiles.

From a logistics standpoint, missiles have an important advantage in precision guidance, which the committee believes is the most important technological route to reducing the logistics burden of ammunition weight and volume. Gun tubes have the traditional advantages of direct-fire and high-fire-rate weapons, as well as a lower *acquisition cost* per round and munition weight per round. (A comparison based on total cost per kill, including indirect logistics burdens for transporting "dumb" rounds in quantity, will reveal meaningful system trade-offs for AAN.)

The Advanced Fire Support System (AFSS), a current DARPA program for close-support indirect fire (e.g., artillery accompanying battle force elements, as opposed to standoff platforms), illustrates the existing missile technology and emerging system concepts. An example of a potentially competitive "gun-tube" technology is the Marine Corps Dragon Fire system. The discussion below of these two systems is intended to explore the state of the art and highlight important logistical issues, rather than argue for or against a general technology (missiles versus gun tubes) or particular system.

For long-range precision artillery, at distances comparable to or greater than those of the "corps artillery" EM gun concept discussed above, missile technology offers an obvious potential substitute for gun-tubes. Cost per kill and nontechnical considerations, such as acquisition competition with other joint-force standoff platforms, may be important factors in deciding whether to develop one or both of these technology options.

Missile Systems for Kinetic Energy Attack on Armor

High velocity KEP ammunition can be used to attack enemy armor using conventional, ETC, and EM gun system technologies, or using missile system technology. The advantages of missile KEPs are that they can kill at longer ranges, use larger projectiles, and enable in-flight guidance. A missile system can also be used for top attack, increasing the potential kill probability against currently configured combat armor (namely, battle tanks).

KEPs traditionally have been gun-launched using direct-fire aiming, which limits them to line-of-sight targeting of the front or sides of an enemy tank, which are usually better protected and harder to penetrate than the vehicle top. However, a ramjet or rocket could propel a KEP warhead over longer distances (over the horizon), and the target impact location could be precisely controlled.

A disadvantage of relying on a missile system in close engagements is that a KEP missile would have to reach a speed of Mach 6 (roughly 2km/s) or more to reach maximum velocities and establish terminal guidance control. An EM gun system that could put the same energy on the target repeatedly would be too heavy for a high-mobility platform. Because of its lighter weight and greater standoff range, the KEP missile would provide the only feasible approach to meeting AAN engagement system requirements.

There appears to be no perfect solution (within the time frame for fielding initial AAN capabilities), and difficult trade-offs will have to be made on the basis of thorough analyses. The Army, which is currently exploring KEP missile technology in the Compact Kinetic Energy Missile (CKEM) Program should ensure that this program and the corresponding work in EM and ETC gun development will produce the data needed for trade-off analyses, including logistics burdens and other performance measures, within the AAN decision window.

General Purpose Indirect-Fire Weapons

The AAN battle force will need one or more lightweight, precision-guided indirect-fire weapons. This requirement meshes well with the intent of the DARPA AFSS program, which is exploring conceptual weapons systems that combine weight reductions and ease of deployment with enhanced fire support. The program objectives of AFSS are to develop and test systems that can provide the rapid response and lethality of existing gun and missile artillery, enhance system survivability, but require significantly fewer personnel and less logistics support. The program's tasks include developing and demonstrating (1) a highly flexible system, including a guided projectile or munition; (2) a remotely commanded, self-positioning launcher; and (3) a command and control system compatible with military doctrine.

The system concept on which the AFSS program has focused is commonly called the Rocket in a Box. This modular rocket system is similar in design to current multiple launch rocket systems (MLRS) but has more firepower, is smaller, has precision guidance, and has lower procurement and life-cycle costs. Because it can operate with no personnel at the container site, it also reduces the need for artillery crews.

The Rocket in a Box design includes four subsystems: Six Pack missiles; a container-launcher unit; a computer and communications subsystem; and a shipping container. The full development of the system will require work on launchers, munitions, seeker-designators, warheads, and guidance and control and propulsion systems. An attractive feature of this design is that the missiles in their container-launchers can be fired immediately by remote control ("cold launch"), which makes every "uncrated" container, whether sitting on a truck, tank, or land site, a potential artillery battery.

Although the charter for the AFSS program seems to cover gun-tube technology as well as missile systems, the program has focused on the missile artillery option. The rationale for this choice was not clear from the materials and briefings the committee received. Presumably it reflects a perception that logistics costs for gun-tube ammunition and crews are high. The economic advantage, however, is not obvious. For comparison, the Marine Corps Dragon Fire concept illustrates a gun-tube technology option that has many of the same advantages for the AAN that the Rocket in a Box has.

Dragon Fire is a robotic mortar system that folds to a mere 18 inches for transport and can remain hidden in defilade on the battlefield until called into action by remote command. It then unfolds itself within three seconds to a standing position, automatically loads its ammunition, and fires. A single gun tube can fire a variety of munitions (packed in a 32-round magazine), including a munition guided by the GPS. The 120-mm tube has a range of 13 km with rocket-assisted munitions (Roos, 1998). Thus, Dragon Fire can provide precision attack capability from a light, portable, relatively inexpensive platform. A similar system to accompany an AAN battle force could provide significant logistics savings in ammunition, crew, and transport for both, compared with traditional crew-served mortar and cannon artillery systems.

Precision Guided Munitions

Whatever launch technology is used, the critical element for hitting the target with every indirect-fired round is precision guidance of the projectile to its aim point. The opening section of this chapter on SA described some of the enabling technologies for precision guided munitions. These technologies can be integrated into different guidance regimes. In some regimes, the target is identified and tracked, aim-point control data for the projectile are computed either at the launch platform or at a target designator located separately from the launch platform, and the projectile and the control data are transmitted to the projectile. For a fast-moving battle force, however, the most useful guidance regimes are those that provide "fire and forget" capability. This means that, at some point during the flight to the target, the components of the projectile itself take over the functions of acquiring and tracking the target and computing path corrections.

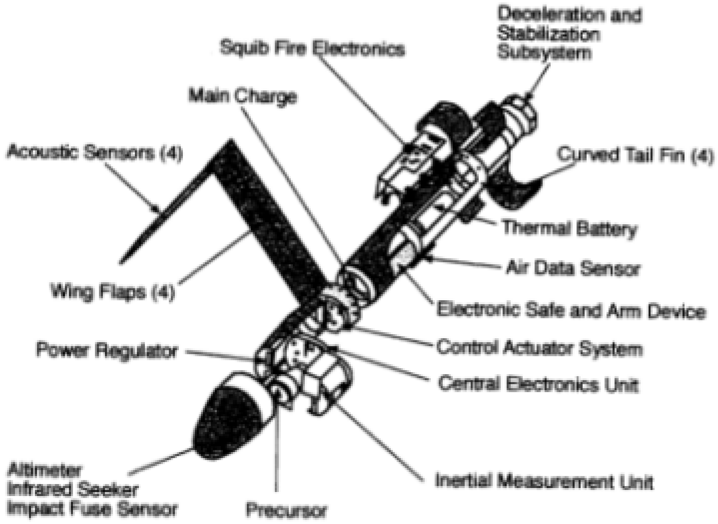

Figure 6-3
Major BAT subsystems.

In this section the committee uses the Army tactical missile system (ATACMS) and the brilliant anti-tank (BAT) submunition to illustrate how the components of precision guidance are assembled in a present day "smart munition." The committee believes that the development of BAT, which began in the early 1980s, is an excellent example of how technology can be used to provide highly reliable, inexpensive, and compact munitions that could cut the logistics burden of ammunition to a fraction of today's requirements. It also illustrates how lengthy the process from conception to fielding is likely to be for AAN systems.

A BAT can locate, attack, and destroy an enemy combat vehicle, including a tank. The kill mechanism involves attacking stationary or moving vehicles from the top, where they are most vulnerable. The BAT airframe, which provides the external aerodynamic configuration for the submunition, contains all of the subsystems to perform the terminal-phase functions for homing in on the target (Figure 6-3). All necessary location and tactical data are downloaded from the parent missile system to the BAT submunitions prior to their release. The control actuator system provides the guidance and control for the submunition, based on control data (commands) from the central electronics unit, which is the computational focal point for the submunition. The central electronics unit integrates all sensor data and mission logic and generates the sequence of computer commands to complete the mission. The computations are based on mission logic software, inertial measurement data from the inertial measurement unit, air speed data from the air data sensor, and acoustic data from the acoustic data sensors. A thermal battery provides electrical power for the power regulator, which in turn supplies and conditions the various electrical voltages required by the BAT subsystems.

After the main missile vehicle releases the BAT submunitions, each BAT deploys a gas-inflated ram air stabilizer (GIRAS) that stabilizes and decelerates the submunition to its operating speed. The GIRAS is then jettisoned, the main parachute deployed, and the wings and tail fins configured. Still attached to the main parachute, the BAT acoustically searches for and detects the target area. Once the target area is located, the BAT cuts itself loose from the main parachute and maneuvers into a specific target area defined by acoustic target detection. When the BAT reaches the target area, a secondary parachute is deployed and the infrared (IR) seeker begins to search for and select a specific target. When the target is selected, the BAT cuts loose from the secondary parachute and glides toward the target using IR point tracking. As it closes on the target, the BAT arms its warhead and selects an aim point, using image correlation. The BAT continues to track this aim point as it guides itself to the target. An impact fuse sensor in the forward section of the airframe detects impact and signals the electronic safe and arm device to detonate the precursor and main charges in the warhead.

This description illustrates the complexity of operations required for a precision guided submunition. Multiple sensing systems are used at different stages for both environmental data (to control flight and staging operations) and target detection and tracking. The control and flight regime is likely to change at each stage; the intelligence to shift from one control mode to the next must be built into the electronics and software. As the variety of targets to be attacked by precision guided munitions increases—either by making the same munition more adaptable or by developing alternative terminal-phase munitions for the same delivery system—the detection and guidance capabilities of the components will have to be increased. As potential adversaries learn how a certain munition is guided, they will hunt for evasive or deceptive counteractions, which will also drive the demand for more sophisticated sensing, processing, and controls. The hardware, software, and firmware to implement these sophisticated guidance systems must be exceptionally reliable, as well as inexpensive enough to keep costs reasonable, relative to the military value of the targets.

Propellants, Explosives, and Warheads

The weight and volume of energetics, the energetic materials used to project a missile to its target (the propellant) and to energize or provide a warhead kill mechanism, contribute directly to the weight and volume of the ammunition logistics burden. Materials with a higher energy density may require smaller, lighter delivery systems. Energetics that are less likely to react to heat exposure or accidental shocks (as opposed to impact on target) may also be used to produce "less sensitive" munitions.[2] Less sensitive munitions reduce logistics burdens by reducing the packaging weight and volume necessary for safe handling and storage. More can be transported in a given volume, because distances between rounds (the magazine separation) can be minimized.

Less sensitive munitions are also less likely to cause "fratricide" accidents (the accidental detonation of one round that causes rounds stored with it to detonate as well). Preventing munitions fratricide not only increases safety but also decreases the logistical requirement for ammunition resupply and for the repair or replacement of damaged munitions and equipment. (Less sensitive munitions are also inherently safer for the

[2] Military Standard 2105 defines an "insensitive munition" as one that passes seven tests specified in the standard. For purposes of this report, the term "less sensitive munition" refers to munitions that have been designed or formulated to be less likely to react to thermal and shock stimuli ("threat stimuli"), whether or not they meet (or exceed) the seven specified criteria for an insensitive munition.

soldiers who move and fire them.) The general challenge, then, is to develop affordable, highly lethal systems that can engage a broad range of targets and, at the same time, reduce the weight and volume of projectiles, missiles, warheads, and launch systems.

The committee identified four areas of improvement in the broad area of energetic and warhead materials that could substantially reduce logistics burdens:

- missile propellants
- less sensitive munitions
- warhead materials and explosives
- multipurpose warheads

In addition to research and development in these specific areas, general enabling technologies including materials processing techniques and analytical design tools (see Appendix C) are needed in all areas.

Missile Propellants

For many AAN operations, explosives and propellant materials and formulations will have to provide higher performance but be less sensitive to shock and thermal threats. For example, missile acceleration will have to increase dramatically over today's standards to achieve a relatively short fly-out time, the Mach 6 and higher velocities required of a missile system roughly equivalent to a gun system for KEP rounds.

Missile propellants for both rocket and air-breathing (jet) propulsion will have to be throttleable, produce minimum smoke and thermal energy, and be less sensitive. For an AAN battle force in particular (but also for follow-on Army forces), missile systems with stealth and agility must be launched from small vehicles—next-generation scout or utility vehicles, as well as AAN combat vehicles.

Solid-fuel ramjet technology uses fuels that are not exotic and uses the air as the oxidizer (a small solid propellant booster is needed to accelerate up to Mach 2). High-speed ramjet missiles could yield high payoffs for a lightweight AAN battle force (see Figure 6-4). Ramjet missiles have high velocities (ca. Mach 6), can be as small as Stinger missiles, and are generally powered all the way to the target. Their range depends on their size. Above Mach 6, cooling does become an important consideration, and new materials would have to be used. Current and future generations of ramjets use gas generator chambers in which the propellant burning rate can be controlled by chamber pressure, resulting in a throttleable missile. However, new propellants will have to formulated that have a broad range of burning rates at safer low pressures to prevent the ramjet from exploding.

The primary benefit of using air-breathing engine cycles in Army missile systems is the increase in propulsive energy over conventional rocket systems. This increased energy can be used to extend range or decrease time to target (or a combination of the two), to decrease the number of launchers required, to provide throttle control to enable "smart" propulsion, and to decrease missile size and weight while maintaining performance levels.

Solid-ducted ramjets reduce maintenance, and liquid-fuel ramjets are available for extended high-speed cruise. Turbine engines are presently in use for long-range subsonic flight. The solid-fuel Air-Turbo-Rocket combines a simple expendable turbine with a ramjet combustor to attain subsonic to supersonic speeds, while maintaining throttle control. For high-speed systems, ramjet engines could upgrade existing missile systems for a fraction of the cost of a new weapons development program and substantially improve performance. Air-breathing engines can be expected to increase the propulsion unit cost by 20 to 100 percent over rocket propulsion. However, considerable savings can be expected at the system level, considering propulsion typically represents on 5 to 10 percent of the missile cost. Other cost factors include reduced procurement quantities because of improved coverage and reduced material losses.

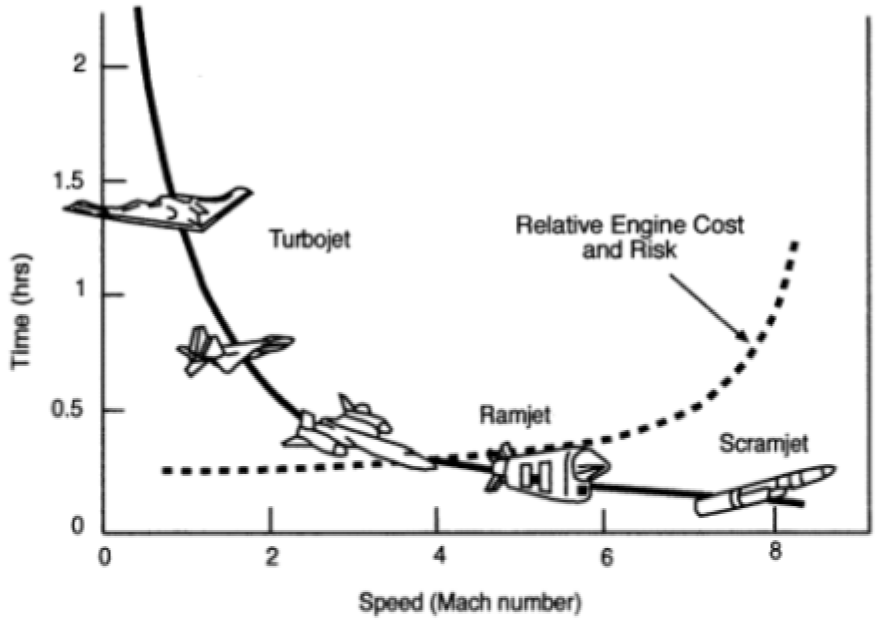

Figure 6-4
Comparison of engine technologies.

Fifteen years ago, many U.S. companies and the armed services were all working on ramjets. Today, only two U.S. companies have expertise in ramjets and, perhaps, only one military program is still active, the Beyond Visual Range Air-to-Air Missile (BVRAAM). In fact, the United States could lose all of its capabilities in this area, even though several foreign countries (Russia, United Kingdom, China, France, India, South Africa, Germany, Israel, and Japan) have ramjet missile systems, active flight testing, or ongoing development programs.

The Army is participating in the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) Program to improve rocket motor performance dramatically. IHPRPT is a cooperative effort of government and private industry, with joint service participation. Its goal is to develop a strategy for doubling U.S. rocket propulsion performance in the next 15 years. Novel propellants and ingredients, higher pressure operating conditions, and multipulse and throttleable motors are all being considered. The committee believes that increased participation in this program, particularly with a clear focus on the needs of AAN systems, would be a good way for the Army to leverage its resources to reduce AAN logistics.

Warhead Materials

The purpose of improving warheads for shaped charges and explosively formed penetrators is to increase the lethality of warheads. Promising materials for the mass element of the shaped charge or penetrator include tantalum, molybdenum, and tungsten. These elements can be coupled with energetics in precise formulations to ensure "one hit, one kill" while decreasing the weight per round. As a prime example, shaped charge performance is strongly influenced by the precision of the explosive. Lethal performance can be increased by improving precision for a fixed energy.

Multimode Warheads

A multimode warhead can produce one of several compact, controllable pattern fragments, depending on the target type. For example, these warheads can be programmed in the field to deliver a single explosively formed penetrator (top attack on an armored vehicle); large chunky fragments (vehicles and other targets); or high blast with very fine fragments (antipersonnel and blast-sensitive targets). To reduce the logistics burden and increase versatility, the Army should continue to support basic work on multimode warheads.

Advanced computerized detonation models are an essential aspect of this research. The Logistics Integration Agency provided the committee with an overview of relevant work at several U.S. Department of Energy national laboratories (Chase, 1998).[3] In 1994, for example, the Los Alamos National Laboratory reported that it had developed metastable interstitial composite energetic materials with the potential for tailored reaction rates with product gas control that could enable warhead fragmentation patterns to be "tuned to achieve a kill while minimizing collateral damage." These materials could lead to smaller and more lethal warheads that reduce logistics burden. Smaller, highly efficient warheads could also be launched from robotic vehicles, such as UAVs or UGVs.

Less Sensitive Munitions

Decreasing the sensitivity of energetic materials and formulations is a difficult technical challenge because increasing the performance of a material as an *energetic* has historically tended to increase its sensitivity. However, if artillery rounds, warhead explosives, and missile propellants were less sensitive to impact and thermal exposure, they would not only be safer to handle, but they would also reduce logistics burdens.

The most important direct consequences in terms of reducing logistics burden would be that packing densities could be increased, the amount of protective packaging could be reduced, and bulk shipping would be less complex. Because less sensitive munitions have less risk of fratricide, fewer rounds would explode accidentally during storage, movement, and handling. Box 6-1 describes the results of a Navy study indicating that the indirect effects on material costs could be substantial, in addition to reducing the risk of death and injuries.

[3] Much of the work in this area is classified.

BOX 6-1 Benefits of Less Sensitive Munitions

The Center for Naval Analyses has studied the effects of insensitive munitions on board aircraft carriers (CNA, 1991). Actual data on deaths, injuries, and materials costs for three accidents (on three carriers) in which no insensitive munitions were involved were compared with the center's estimates if the best existing technologies (at that time) for reduced sensitivity had been in use.

Consequence	Actual (no insensitivity)	Estimated (insensitive)	Reduction
Deaths	176	72	59%
Injuries	552	63	89%
Materials Costs (1999 $ million)[a]	$1,966.50	$469.60	76%

The absolute numbers for three incidents may not carry over from Navy to Army environments; aircraft carriers are much more expensive than Army combat platforms, and the personnel density aboard ships is very high. Nevertheless, the percentage reductions indicate that even with 1991 technology, which has since been improved significantly, less sensitive munitions could mean major improvements in safety and reduced damage.

[a] Reported cost data for fiscal year 1991 increased at 4 percent per year to fiscal year 1999.

There are many ways the Army could decrease the sensitivity of its munitions, even with current technologies. Many Army warheads still use either pressed HMX (high melting explosive) (up to 98 percent) with a binder or melt-cast explosive formulations, such as Composition B (RDX [rapid detonating explosive] and TNT [2,4,6-Trinitrotoluene]) or Octol (HMX and TNT). All of these formulations are much more shock sensitive then improved formulations and will detonate when exposed to shocks of 14 to 28 kbar. Figure 6-5 illustrates the roughly threefold decrease in shock sensitivity attainable by replacing these formulations with *existing* PBX (plastic-bonded explosives) that have the same performance characteristics as energetics.

The Large Scale Card Gap Test on which data in Figure 6-5 are based uses a standard apparatus and procedure prescribed by Naval Ordnance Laboratory Technical Bulletin 700-2. A donor charge that produces a known shock pressure is detonated against the explosive to be tested. If the donor charge detonates the test explosive when in direct contact with it, cellulose acetate cards of a standard thickness (0.01 inch) are placed between the donor charge and the test explosive. Each card attenuates the shock pressure by a known amount, represented by the curve in the graph. The point on the curve where a given explosive formulation is detonated but at which one more card causes no detonation, is the score for shock sensitivity in this test. For the test results illustrated, conventional Army warhead explosives had test scores of 14 to 28 kbar. PBX alternatives had test scores of 50 to 69 kbar. (Bernecker, 1988).

Beyond the substantial improvements that could be made simply by adopting the best current technologies, the development of improved energetics must be recognized as a *system design* problem. Army missile propellants and explosives will have to be less sensitive to both temperature and shocks and have higher specific energy (energy per unit mass and volume) and other performance values. In decreasing the sensitivity of munitions, many factors will come into play. Shock sensitivity is usually reduced through changes in formulation and processing techniques. Reductions in thermal sensitivity usually require sophisticated changes in engineering design of the fill configuration and casing to provide adequate venting under either slow or fast heating rates. Energetics performance and sensitivity to diverse threats must be considered in the context of increasing the accuracy of targeting through precision guidance and SA.

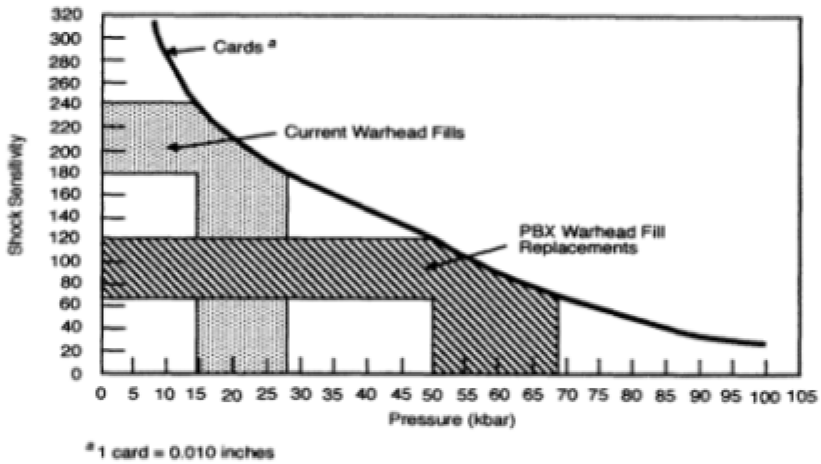

Figure 6-5
Calibration curve from large-scale card gap tests of conventional warhead explosives used by the Army and PBX replacements. Source: Bernecker, 1988.

Smokeless rocket propellants are being developed today that have increased specific impulse but are less sensitive to shock. Plastic-bonded explosives dramatically reduce shock and thermal sensitivities. For example, the Air Force warhead explosive AFX-235 has the performance characteristics of an explosive that contains 96 percent (by weight) HMX, although it contains only 75 percent HMX in an energetic plastic-bonded binder. Shock-sensitive weapons or munitions could be more closely spaced by the clever use of mitigating materials (closely related to the development of armor materials) and by unique packaging layouts based on computerized shock models. Thermal threats could be mitigated by active or passive venting. The Navy has implemented a variety of concepts for less sensitive munitions, including the strategic use of barriers and mitigators. The Army, however, has only begun to recognize the logistical (and safety) implications of reducing munitions sensitivity.

In terms of logistics burdens, more rounds can be stored in the same area if they are less sensitive, or an equivalent number of rounds (or equivalent amount of lethal force per projectile) can be stored in a smaller area. Platforms and operations can be designed to allow personnel and equipment to operate in closer proximity to ammunition stores. The chances of transportation or handling accidents would be reduced, as well as the logistics and operations planning margins, and the safety of Army personnel would be increased. If the AAN process forces the Army to design for the best *systems solutions* for achieving diverse performance goals, including substantial reductions in the logistics burdens of ammunition and lethal systems, the Army will have a golden opportunity to make decreased munitions sensitivity a serious cost trade-off.

Logistics Implications of Projectile Weapon Systems

The foregoing discussion has only touched on the surface of potential system and application concepts, their potential logistical consequences, and the technological opportunities and issues relevant to providing projectile weapons for an AAN battle force. Even this limited review, however, demonstrates that there will be no obvious winners among the alternative systems. In many instances, data are not sufficient to make quantitative comparisons, *particularly with respect to the logistical implications of an entire weapons system concept.* Should an AAN "main combat vehicle" be armed with an ETC gun, an EM gun, or an improved missile system? Which alternative has the least logistics burden for an implementation that could be *in the field* by 2025? Would a general switch to liquid propellants meet AAN engagement needs while reducing logistics burdens? Which approaches to precision guidance will guarantee that every round hits its target? The answers to these and other questions will be required to support design decisions that must be made by 2010, 15 years before the AAN becomes a reality. The general argument advanced in Chapter 3 for a systems engineering approach to logistics trade-off analyses will be crucial for selecting new projectile weapons for AAN.

Current Army and joint programs run the gamut of research and development in the technologies for projectile weapons. Except for some of the electronics for enabling precision guidance, nondefense commercial markets will not take the lead or be a source of innovation. However, the Army can *leverage the R&D program base in projectile weapons that already exists.* The goal of many of these programs was, and still is, increasing lethality, not reducing logistics burdens. Fortunately, "one round, one hit, one kill" has substantial implications for both. But these programs have different constituencies responding to different requirements. Even for nonlogistical performance objectives, there are no *common* criteria for program success. The Army should try to coordinate resources from these programs for trade-off analyses of AAN engagement systems.

First, the Army will have to formulate the questions about AAN performance capabilities that must be answered in terms that apply to the candidate projectile weapon systems. These performance capabilities must *include logistical performance as a primary objective, not as an afterthought.* Second, each existing program that supports a weapon system concept must be evaluated to determine whether, and in what time frame, it might provide answers—or the data needed to model solutions that will provide the answers—to those questions. Finally, the Army should make adjustments to programs to ensure that answers will be available in time for AAN decisions on system designs. In many cases, existing concept demonstration programs will have to be modified to ensure that they provide sound data on logistics support requirements that can be fed into platform models and engagement models in the M&S hierarchy described in Chapter 3. If the current state of knowledge cannot support a technical basis for acquiring essential data empirically or for constructing a validated simulation to model it, the Army might have to support applied or even basic research.

DIRECTED ENERGY WEAPONS

Directed energy weapons, which use electromagnetic radiation as their lethality mechanism, include laser, high-power microwave, and high-power millimeter wave systems. Because their lethality mechanism is the transfer of energy from this radiation to the target on which it is focused, there is no mass or volume of ammunition, as there are with projectile weapons. Instead, the logistics burdens are the fuel and energy to supply the high power demands of these weapons, the weight and volume of the pulsed power subsystem that stores and transfers electrical energy, and the weight and volume of the subsystem that creates and directs the pulses of radiation at the target. For weapons systems that accompany an AAN battle force to the area of operations, the energy needed to recharge the pulsed power storage subsystem must be supplied by the battlefield fuel carried with the battle force or by some other store of energy, such as primary batteries. The conversion of fuel energy to electrical energy for the weapon power supply must be included in the sizing of the system that does the conversion—most likely the power plants in combat vehicles.

Barring an unanticipated paradigm-altering discovery about the fundamental physical mechanisms on which directed energy technologies are based, the committee believes the position stated in the *STAR 21* study remains valid. In the AAN time frame, directed energy weapons will be feasible options as *tactical systems* for antisensor, antiprecision guidance, and anti-SA weapons. It will not be feasible to develop directed energy weapons systems for heavy-duty structural attack, particularly for the highly mobile operational concepts envisioned for an AAN battle force. The *STAR 21* report predicted that "heavy-duty directed energy weapons for vehicle kill against aircraft, missiles, and spacecraft are likely to develop first, if at all, as strategic defense systems" (NRC, 1992, p. 86).

Transportable versions of directed energy systems, probably developed for the defense of the continental United States, might eventually be usable in an AAN staging area, if adequate energy were available and if the battle force operation was vulnerable to antisensor and anti-SA weapons. From the standpoint of reducing logistics burdens for an AAN battle force, however, tactical directed energy weapons would *complement and supplement* projectile weapon systems, not replace them. Therefore, they represent a separate and *additional* class of logistics burdens.

Lasers

Various types of lasers have potential as offensive weapons against small and large protected targets, but they would require very high power densities and durations on target, as well as a direct line of sight to the target. The Night Vision Electronic Sensors Directorate of the Army Communications-Electronic Command (CECOM) has defined a notional directed energy warfare vehicle (DEW-V) that could serve as a "virtual test-bed" to determine the operational effectiveness of vehicle-mounted directed energy weapons for battle scenarios in 2015 and beyond. Although there is no hardware development plan, the concept may be expanded to include development of a DEW-V around an Abrams tank chassis or a Bradley fighting vehicle chassis for Army XXI (Knowles, 1996).

Because lasers use discrete wavelengths (primarily in the IR region), care must be taken to avoid wavelengths that can be degraded by atmospheric conditions. For example, the Navy stopped work on its high power deuterium fluoride laser because the laser could not accommodate extreme environmental conditions (Knowles, 1996).

A more practical use for lasers and other electromagnetic radiation beams, achievable in the near-term, is to use them as antisensor weapons to disable the enemy's sensors and defend against enemy projectile weapons. The electro-optical sensors used for precision guidance of smart munitions are vulnerable to laser attack. Tactical lasers that can put energies on the target of more than 1 kJ are feasible. Tactically useful free-electron lasers (FELs) in the megawatt power range may be possible, although to date only low-power FELs have actually been built (Knowles, 1996).

One disadvantage of using lasers, even as tactical antisensor weapons, is the political and geopolitical ramifications of their use. Because they can cause permanent eye injury, lasers have been banned by international treaty agreements. Because current electro-optical sensors are also vulnerable to laser attack, both the CECOM and the Natick Research, Development and Engineering Centers have been working on notch filters to protect human eyes and electro-optical sensors from the discrete wavelengths used by lasers.

The principal enabling technologies for laser weapons are efficient high power generators, efficient lasers, infrared sensors, and advanced processors and target extraction algorithms (DoD, 1998a). All of the services, and many of the national laboratories, are currently conducting research on lasers. The Air Force in particular has an extensive airborne laser program. The committee recommends research groups involved in these programs coordinate to leverage resources and avoid wasteful duplication. For a laser antisensor weapon to be incorporated into AAN combat vehicles, the power requirements for the laser and the sizing of the weapon system will have to be known before the Army can make realistic estimates for modeling its vehicle design (see Chapter 5).

Microwave Devices

Smart weapons that depend on electronic components for precision guidance are vulnerable to high-power electromagnetic energy that overheats these components to the point of breakdown. Therefore, directed energy weapons are prime candidates for defensive applications. The effects of high-power microwaves (HPM) on electronics are similar in this respect to the electromagnetic pulse (EMP) from the detonation of a nuclear warhead, except that the HPM frequency range (0.5 to 100 GHz) is significantly higher. These microwaves can penetrate electronic systems either through the target system's antennas or through energy leakage into electronics enclosures. With its high frequencies, HPM can destroy electronic components that would not be affected by a nuclear EMP pulse. HPM weapons could disrupt or damage communication systems and the electronic subsystems of weapon systems, smart munitions, and airborne or ground vehicles.

HPM could also affect friendly forces. For example, stealth coatings are designed to absorb microwaves, and an HPM pulse could have a thermal effect much like the effect of a microwave oven. Another drawback of HPM weapons is that the antennas will have to be large and located in the enemy's line of sight. These antennas have a significant EM signature, which would make them easy for an opponent to find and attack (Herskovitz, 1993).

High-power millimeter wave (HPMM) systems also appear to have great potential. In short-range engagements (2 to 5 km), the power densities at the target would be almost the same as at the antenna. An advantage of millimeter waves over laser systems is that they can be used under a wider range of weather conditions. Progress continues to be made in the development of HPMM generators. The principal enabling technologies for HPMM weapon systems are efficient power sources, HPMM generators, precision large antennas, advanced passive electromagnetic sensors, and advanced processors and target extraction algorithms (DoD, 1998a).

LESS-THAN-LETHAL WEAPONS

Like today's Army, the AAN will face a wide array of adversaries. With "less-than-lethal" (LTL) weapons, the battle force would be able to make a measured response to an attack or provocation, facilitate the *control* of opposing forces, and avoid collateral casualties in situations, such as urban warfare. These objectives are very different from the objectives of *destroying* opposing forces with projectile weapons, which have the unfortunate side effect of harming noncombatants who happen to be in their effective range. LTL weapons include sticky foams, stun guns and bombs, bright-light flashes, and rubber bullets that can temporarily incapacitate opponents. Other techniques for controlling populations are disrupting communications and degrading infrastructure. Much of the technology development for less exotic LTL weapons has been led by the U.S. Department of Justice and civilian law enforcement agencies, mainly for crowd control or for use by special teams in hostage situations.

A unique LTL approach with applications to urban warfare may be to capitalize on resonances with the human body. For example, the resonant frequency of a human chest cavity is about 20 Hz, and the frequency of brain waves is between 1 and 40 Hz. Matching those frequencies "resonantly" with a high-energy source could instantly incapacitate someone. A prototype pulse detonation engine has a frequency of about 15 Hz. The sound power level from this engine is extremely high—on the order of bels, rather than decibels, and resonant coupling with brain waves could seriously impair an adversary. A war-fighter would not have to be in the area of the conflict for this device to be effective.

Like directed energy weapons, LTL weapons are likely to complement and supplement projectile weapons rather than replace them. Therefore, they will often add to logistics burdens by increasing the numbers and variety of systems required in the battle force's inventory. However, logistics efficiencies could be achieved by including logistics considerations in the design and development of LTL weapons.

SCIENCE AND TECHNOLOGY INITIATIVES TO REDUCE LOGISTICS BURDENS OF ENGAGEMENT SYSTEMS

Based on the preceding analyses of the logistics burdens associated with engagement system options for AAN battle force operations and the technological opportunities for reducing these burdens, the committee concluded that the Army should pursue the following areas of scientific research and technology development. The order of the numbered items under a heading reflects a rough order of priority.

Situational Awareness

1. Continuation of SA Technology Insertion beyond Army XXI. Technologies that support near-perfect, near-real-time SA will be critical enablers for AAN engagement systems. The direct and indirect consequences of ensuring SA range from enabling effective support from standoff platforms, being able to deliver "just the right amount" of logistics, and the right-sizing of battle force elements to providing the battlefield intelligence required for "one round, one hit, one kill" precision in indirect-fire engagements. SA will thus be the single most significant determinant of both AAN combat effectiveness and the reduction of logistics burdens.

Rapid innovations in the underlying technologies, most of which will continue to be driven by commercial market forces beyond the control of the military, will provide opportunities for improving SA but will also force the performance levels to rise continually for maintaining *technological overmatch* against potential opponents. The Army should not assume that "digitizing" the Army XXI force, through introduction of today's (or even the next decade's) state-of-the-art technology for information acquisition, processing, distribution, and representation, will suffice for the AAN in 2025. To ensure that AAN battle forces always have superior SA, the Army will have to find ways to upgrade the underlying technologies incrementally, within resource constraints, while maintaining system integrity.

2. Precision Guided Munitions. The precision guidance of projectiles (or other weapons effects, such as directed energy or LTL weapons) is the primary means of reducing the ammunition logistics burden. This burden has traditionally been second only to fuel in the weight and volume required per unit of combat effectiveness. As the battle space defined by lethal reach expands spatially but shrinks in time, precision guidance technologies will determine how well a force can effect "one round, one hit, one kill." Much of the information on state-of-the-art technologies and research to improve guidance systems is classified and, therefore, not available for this study. The committee assumes that the Army will continue its support of precision attack systems for the AAN.

3. Vulnerability of SA to Cascading Failure. A weakness or flaw in the technology on which SA depends could have catastrophic consequences if the system is vulnerable to single-point failure—or even to multiple-point failure. The commercial markets that drive many of the core technologies for SA subsystems and components can tolerate more vulnerabilities than the Army—and the national defense generally. To the extent that SA elements are joint systems, the Army should encourage, and even demand, joint efforts to ensure that the AAN battle force is not defeated because of an SA failure stemming from a flaw in a communications network, computer operating system, or other technology built from commercially developed components. The same rigor will be necessary for SA elements developed and controlled by the Army. During AAN war games, the Army should allow the opposing forces to attack SA infrastructure and should model the failure of different SA elements to uncover vulnerabilities.

Projectile Weapon Systems

1. Logistics and Performance Trade-off Analyses for Projectile Weapons. The committee found no clear, obvious winners among the potential alternative technologies for the main armament of an armored AAN combat vehicle or close-support artillery. Even on the level of broad technology options, such as liquid propellants, the available information is insufficient to make an informed choice, either on the basis of logistics burdens or trade-offs in which logistics is included with other performance characteristics. To remedy this situation, the Army should leverage the existing research and development program base in projectile weapons and supporting technologies to obtain data for modeling system alternatives and making well grounded trade-offs. Data on logistics burdens should be among the required data about each enabling technology or system concept. By assessing disparate programs and developments from the standpoint of their contributions to the hierarchical simulation of system options and making informed design trade-offs, the Army will be able to determine where modifications or additions to the science and technology base should be made.

2. Systems Design Approach to Increasing Lethality of Energetics and Warhead Materials while Decreasing Weight, Volume, and Sensitivity. The most important enabler for reducing the logistics burden of ammunition (after precision guidance of munitions) is to increase (or at least maintain) lethal effectiveness per round while decreasing the total logistical weight and volume per round. The complexity of the issues, diversity of performance objectives, and broad range of technological opportunities will require a systems design and trade-off approach to achieve the best combination of technology for AAN needs. For example, the Army needs missile systems that are small and affordable enough to be incorporated into large numbers of smaller vehicles. The missile propellant(s) for such systems must enable higher acceleration, minimum smoke, less sensitivity to shock and thermal threats, and capability for precision guidance (i.e., controllable burn rate). New energetic materials and formulations must increase energy (or rate of energy release) per unit mass and volume of propellant or warhead explosive, while making the munition less sensitive. More effective warhead materials and multimode warheads can increase lethal effectiveness by ensuring that each hit is a kill. As the Army looks for ways to focus and strengthen its program to improve energetics and decrease their sensitivity, it should attempt to leverage the very active Navy program in this field.

Directed-Energy and Less-than-Lethal Weapons

1. Directed-Energy Weapons to Supplement, Not Replace, Projectile Weapons. The committee agrees with the *STAR 21* study, which predicted that tactical directed-energy weapons would not be feasible for heavy-duty structural attacks on opposing platforms, weapons, or missiles and projectiles in the 2025 time frame. The logistics implications of these weapons—in terms of system weight and energy requirements—also preclude their consideration as weapons for an AAN battle force. However, tactical directed-energy weapons that can attack sensors, guidance subsystems, and electronic components are likely to be ready and useful for AAN operations. These tactical weapons would supplement, but not replace, projectile weapons. Their logistics burdens, therefore, constitute a separate class from those of projectile weapons.

2. Less-Than-Lethal Weapons to Supplement Projectile Weapons. LTL weapons for use in special situations, such as urban warfare, or for incapacitating opposing troops will be another supplement to the AAN engagement arsenal. From the standpoint of logistics burdens, however, they are not an alternative to projectile weapons.

7

Reliability Concepts

The AAN battle force concept is predicated on all systems being highly reliable. Furthermore, to reduce logistics demand the Army must make reliability an equal partner with lethality, survivability, and mobility considerations. This chapter describes the reliability concepts and technologies needed to develop AAN mission-reliable systems.

LOGISTICAL IMPLICATIONS OF HIGHLY RELIABLE SYSTEMS

Improving the reliability of the systems used by an AAN battle force will have a multiplier effect on reducing logistics demands. This multiplier effect can be illustrated by reviewing two functional requirements arising from the assumed AAN concept for logistics support. First, as briefed to the committee, the AAN battle force will take no separate maintenance and supply units into the area of operations. Second, a battle unit support element (BUSE) located at the staging area will be responsible for rapid refitting, refueling, and repair of battle force systems between combat pulses in preparation for subsequent pulses. From these two functional requirements, it is clear that decreasing the maintenance and spare parts needed for subsequent pulses are essential aspects of AAN reliability. Thus, the functional requirements can be used to help define the essential degree of reliability and the things that are unnecessary or too costly, even if they are desirable in principle.

The classic definition for the reliability of an item, system, or component is the probability that it will operate successfully during its mission (see Box 7-1). A typical AAN battle force mission will require systems that are at least reliable enough to meet the two functional requirements described above. No doubt, other functional requirements for AAN systems will also generate reliability requirements, but these two basic requirements are sufficient to illustrate that (1) improving reliability reduces logistics demand and (2) *the reliability of any system is relative to the mission context in which it is expected to operate.*

Pulse-Reliable Systems

For the AAN assumption of no maintenance and repair support in the battle space during an operational pulse, all systems must be reliable enough for commanders to meet their force readiness and deployment timelines.

BOX 7-1 Classical Definitions of Reliability and Related Concepts

Reliability. The probability that an item, component, or system will operate successfully during its mission.

Maintainability. The probability that an item, component, or system will remain in a specified operational condition or can be restored to that condition within a given period of time, when maintenance is performed according to prescribed procedures and resources.

Availability. The probability that, at any random instant, an item, component, or system will be in proper condition to begin a mission.

Durability. The probability that an item, component, or system will successfully survive its projected service life, overhaul point, or rebuild point without a catastrophic failure. (A catastrophic failure is a failure that requires that the item, component, or system be rebuilt or replaced.)

For a combat operation to accomplish its objectives, all systems taken into the area of operations must be close to fully operational and require neither repair nor maintenance throughout the period of the operation. Systems must not fail during that operational time period. Even in a dynamic, high-stress environment, all systems must maintain a high level of operability, even if a part or component has been damaged or malfunctions. For the purposes of this report, an AAN system is *pulse-reliable* if it meets the following criteria:

- requires no maintenance or wear-related repair or replacement by external logistics personnel for the duration of a combat pulse
- can continue to perform within minimum operational parameters even with damage to subsystems

If all AAN systems are pulse-reliable, no maintenance and repair support elements—troops, tools, or spare parts—would have to accompany the combat elements. It follows that no fuel, food, water, or shelter would be needed for support elements, and no combat capability would have to be diverted to protect them. No transport systems, which have their own logistics requirements, would be needed to bring in and retrieve the support elements. If commanders could rely on the pulse-reliability of their combat systems, the effectiveness of a force of any given size would be increased for planning purposes. In other words, a given objective could be met with a smaller force, requiring proportionately less fuel, ammunition, etc. These indirect effects of pulse-reliable systems are based on the assumption that every system taken into a combat operation will perform successfully for the duration of the operation.

Fast Refitting through Improved Maintainability

The pulsed operations of an AAN battle force will require that the refueling, refitting, and repair phase of each cycle be short enough to keep an opponent off guard and incapable of regrouping and responding effectively to the next combat pulse. AAN systems will require maintenance and repair, but the speed with which a returning battle element can be reconstituted to a state of pulse-reliability and readiness will determine how short this part of the cycle can be. In this context, the overall mission reliability of a system depends on *improved maintainability,* including longer times between preventive maintenance cycles, faster diagnosis and repair or replacement of parts, and preventive or predictive (prognostic) maintenance, rather than reactive maintenance. This performance goal will be called "fast refit."

The logistics impacts of fast refit include (1) fewer maintenance personnel in the BUSE per unit of combat strength required for a given refitting (higher tooth-to-tail ratio); (2) fewer spare parts per average combat-day, including fewer spare systems to replace systems that cannot be repaired before the next pulse; (3) reduced logistics burdens (fuel, food, water, and energy) at the staging area to support a smaller maintenance element; and (4) simpler planning requirements to ensure that the BUSE can sustain the war-fighting operations.

AAN Mission Reliability Versus Ultrareliability

The discussion above shows how the reliability for AAN missions, or *AAN mission reliability,* can be analyzed into specific reliability requirements for systems, such as pulse reliability and fast refit. These requirements can also be expressed as objective, quantifiable measures, or *performance metrics.* A hypothetical example of a metric for pulse reliability would be a 90 percent level of confidence that a system verified as pulse reliable will be able to meet eight standards for full operating performance throughout the duration of a 14-day pulse, with a 99 percent level of confidence that it will perform at a degraded (but still operable) level of performance for no more than two of those measures during a pulse. The fast refit requirement might be expressed as an availability metric, such as a 98 percent probability that a given system will be available for the next pulse (pulse reliable and ready) after 12 person-hours of maintenance and refitting, if no battle damage was sustained in the previous operation. The details of both of these hypothetical reliability metrics depend on the specifics of how an AAN battle force would fight and be sustained for the duration of a campaign. Exploring other AAN operational concepts will reveal additional elements of AAN mission reliability.[1]

Basing reliability on how an AAN mission would be conducted is very different from the idea of "ultrareliability," which is too often sold as a context-free property that can be achieved by adopting a particular technology or design. But the concept of ultrareliability is too general to help achieve AAN mission-reliable systems. For this

[1] For example, an analysis of the soldier-machine interfaces required for the complexity, tempo, and intensity of an AAN operation in a three-dimensional battle space would reveal important features of what might be called "trainability": the ease with which a system operator can attain and maintain a high level of proficiency for a specific mission profile.

reason, the committee decided to avoid the term ultrareliability and to focus on AAN mission reliability, that is, the minimum reliability requirements that can be used in a distributed M&S environment to develop AAN systems.

AAN Mission Reliability and RAMD

Reliability, availability, maintainability, and durability (RAMD) have become linked as key factors in keeping future systems affordable, both in terms of investing scarce dollars for research, development, testing, and evaluation (RDT&E) and in terms of fielded equipment that can be procured in adequate quantities within budgetary constraints.[2] The system characteristics that contribute to RAMD are sometimes contrasted with operational performance values because, in the past, performance has typically been achieved *at the expense of RAMD.* AAN mission reliability, however, cannot be separated from other aspects of system performance. *Systems that fail to meet reliability requirements will also fail to meet AAN mission objectives.*

Three approaches can be used to ensure that AAN mission reliability (and related RAMD qualities) receives appropriate consideration along with other performance objectives. First, RAMD qualities must be interpreted into objective, assessable characteristics that can be *designed into* a system. Rather than being lumped together as a vague quality to which lip service is paid with terms like "ultrareliability," *RAMD must be defined in terms of concrete metrics that reflect operational requirements.* System designs should be assessed and engineered against these metrics, just as they are against metrics for mobility, lethality, or any other performance requirement. Second, these objective characteristics must be weighed, along with other performance characteristics, in system trade-offs when designs or prototypes cannot meet all performance goals.

The third approach is a longer-term alternative to the second. Instead of being forced to trade off a desirable level of performance (whether in a reliability measure or some other goal, such as cross-country mobility, lethality, or survivability) to achieve the optimum performance for all performance characteristics, new technology and new design concepts can be developed to improve overall (combined) performance. In short, the third approach is to *seek new and better solutions.* Applied and basic research, when informed by the specific characteristics required to meet difficult AAN system constraints, can, in time, provide new solutions. These three approaches are not mutually exclusive. All three are likely to be needed for complex systems with demanding performance requirements.

The M&S environment described in Chapter 3 provides a near-term implementation of the first two approaches: designing systems for AAN mission reliability and making system trade-offs that do not sacrifice reliability to other performance goals. M&S is an essential and powerful tool for systems engineering to move AAN mission reliability off the bullet charts and into the battle force. The next section describes the necessary elements for a distributed, hierarchical federation of M&S tools adequate for building AAN mission reliability (or "RAMD for AAN") into each system at every

[2] Sometimes adaptability is added to these four characteristics, making the acronym "RAAMD." The argument made here applies to RAAMD, as well as to RAMD.

level, from subsystems down through components, structures, and materials. After that, ways to enhance the third approach are discussed.

USING AN M&S ENVIRONMENT TO DEVELOP AAN MISSION-RELIABLE SYSTEMS

Designing systems and performing trade-off analyses with tools that can simulate whether feasible systems, subsystems, components, and structures will meet mission-specific RAMD metrics is the key to a realistic strategy for achieving AAN mission-reliable systems by 2025. A hierarchy of model domains, illustrated in Figure 7-1, can be constructed for any complex system developed for the AAN battle force. Note that Figure 7-1 is based on the discussion in Chapter 3 of the distributed M&S environment illustrated in Figures 3-1 and 3-2. Fielding AAN materiel in 2025 will require that engineering and manufacturing development begin by 2010. To meet this milestone, extremely complex system trade-offs will have to be made, and the supporting technologies for engineering and manufacturing development will have to be available. In the judgment of the committee, the only way to perform the systems engineering essential to making trade-off analyses while reducing the costs, in time, resources, and risk, of trial-and-error developmental approaches is to use the simulation techniques described in Chapter 3, beginning with conceptual design. This approach is used extensively by leading manufacturers to design highly reliable subsystems and can be effectively exploited by the Army to significantly enhance the reliability of AAN systems.

Unfortunately, existing M&S tools cannot feed data on achievable reliability and performance levels at the component and subsystem levels back to the operational level, at which system trade-offs should be made. Without performing iterative simulations up and down a hierarchy of M&S tools, as illustrated in Figure 7-1, determining through M&S whether a design concept will meet AAN mission reliability objectives will be impossible.[3]

Reliability (much less the pulse and mission reliability needed by AAN systems) is not currently part of the design process, but it can be easily included by adding reliability analysis at appropriate levels of the M&S hierarchy. Designing candidate AAN system concepts to meet AAN mission reliability requirements will require the following extensions of current capabilities and design approaches:

- M&S systems must be *adequate at every level* in the hierarchy at which "designing for reliability" is done, from the top level of force-on-force engagement down to the lowest level at which the reliability of design options is evaluated.
- *Metrics for reliability* at each level must be defined in terms of operational requirements, so that reliability can be assessed objectively at that level.
- The design process must include *iterative simulations* up and down the hierarchy.

[3] For the argument supporting this point, see "M&S Environment to Support AAN Logistics Trade-off Analysis" in Chapter 3.

- At the lowest level at which M&S is being used, *valid data on alternatives* must be available for the characteristics that determine reliability at that level (i.e., estimates of the metrics for reliability at that level of system decomposition must be realistic, not guesses or wishful thinking).
- During the iterative design process, and subsequently during engineering development, testing, and evaluation, the mission reliability of the system (i.e.,

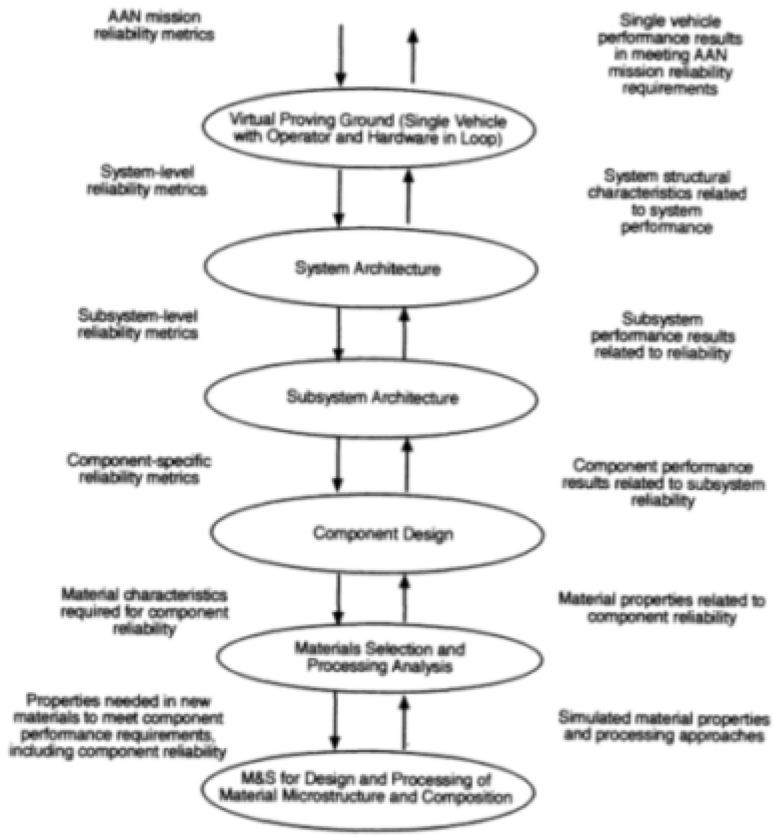

Figure 7-1
Hierarchy of model domains. An extended M&S environment can be used to design reliability into AAN systems, perform system trade-off analyses, and develop new options for enhancing reliability.
The figure is based on Figures 3-1 and 3-2. For the sake of simplicity note that the top two engagement levels are not shown. Also, the requirements and metrics for other performance goals (left side of Figure 3-1) and M&S results relevant to them (right side of Figure 3-1) are not shown.

the reliability-related minimum requirements set for the top level of system performance in simulated AAN engagements) must not be traded away to sustain or increase another desired aspect of overall system value.

In practice, each of these extensions can be achieved in varying degrees. Therefore, the extent to which AAN systems can be designed for reliability will depend on how well the M&S environment and the methodology of using it meet these five goals. The challenges and opportunities in these five areas are explored below.

Adequate M&S Systems

Chapters 3 and 5 examined at length the existing *mobility* M&S systems at each level in the hierarchy, diagnosed some of their limitations, and recommended improvements. Because AAN mission reliability is a cumulative outcome of complex system-level behaviors, it will be helpful to consider the necessary capabilities of each M&S system type described in Chapter 3 to provide a reasonable simulation for assessing reliability.

For example, at each of the three engagement levels shown in Figure 3-1 (forceon-force, multiple systems with operators, and single system with operator), both the normal or "expected" duty cycle and the frequency-versus-severity profile of excursions from the normal cycle must be realistically simulated and exercised. At the system and subsystem levels, the models must include system-stressing loads and conditions and variable patterns of operation, not just baseline operating scenarios. Because time is often a key factor in the appearance of failure modes that reduce reliability, either the simulations at each level must be run for durations required by AAN-mission reliability or the analytical methods used to extrapolate from shorter run times to the durations characteristic of AAN operations and duty cycles must be validated.

Because reliability is relative to context (e.g., mission or duty-cycle profile), the realism of the higher-level models in the hierarchy will be critical to using an M&S environment for designing reliability into an AAN system. In effect, a systems engineer will have to rely on the results from the higher-level models to define the behaviors of the subsystems, components, and materials critical to making the entire system mission reliable. One may, of course, rely on engineering experience or rules of thumb to make a reasonable guess at characteristics that will affect reliability at higher levels of system integration. But these approaches are difficult to quantify into metrics or validate. Reliance on qualitative and heuristic approaches to reliability has probably contributed to the ease with which *reliability has typically been traded away for performance characteristics that could be more easily quantified* during requirements specification, design, and evaluation.

Defining Reliability in Measurable Characteristics

Once mission-specific reliability is accepted as a performance value that applies at each level of an M&S hierarchy, each level will require that appropriate reliability measures be specified for which model runs can be evaluated. Less obvious perhaps is that the appropriateness of the reliability measures at one level is determined by the performance properties at the next higher level to achieve the reliability characteristics required there. This linkage of the reliability measures at a given level to the required performance characteristics for reliability at the next higher level makes it possible for *assessable* reliability requirements to "flow down" from mission-specific, functional requirements (like pulse reliability or rapid refit) to reliability requirements for particular subsystems and components. The linkages between levels enable systematic design to achieve the ultimate (i.e., top level) reliability requirements.

As noted in Chapter 3, the absence of this linkage in existing models prevents the flow of lower-level data up to the systems level in the hierarchy, where alternative designs and trade-offs of one system value for another ought to be made. To state the problem in practical terms, the value of using iterative M&S cycles as an alternative to trial-and-error cycles of design, building, testing, and modifying depends on how closely the M&S hierarchy can model the causal relations between the metrics for reliability at one level and the properties at the next higher level of integration that affect system performance.

Iterative Simulation

In Chapter 3, the committee stressed the importance of iterative simulations up and down the M&S hierarchy. As a high-level system requirement, AAN-mission reliability is a good example of why the iterative approach is essential for making design decisions. (Performance characteristics defined at the system level for such things as energy management, mobility, and lethality require an iterative approach for the same basic reasons.)

A model by its nature is not an exact replica of the thing it models. When a general model is applied to a specific case (for example, when a force-on-force model is used to simulate a particular type of AAN mission or the NRMM is used to simulate the behavior of a particular vehicle concept over selected terrains), the fit of the model can be improved if input parameters are specified and the settings selected for the model's run parameters. If the concept to be modeled is at an early design stage, results from earlier runs can be used as feedback to "refine, tune, and tweak" both the model and the design being tested.

Reliability outcomes of detailed engineering model runs for a combat vehicle (for example) indicating that loads on a bearing approach or exceed design limits may lead to a redesign of the vehicle. Systems that are frequently or easily defeated in a force-on-force simulation or that consistently run out of fuel or ammunition may require that the system be redesigned or modified, that tactics for using the system be reconsidered, or that the training for operators be changed. Another alternative is that the validity of the model itself may be questioned, leading to corrections and refinements in the model.

In an M&S hierarchy of tools, this feedback process extends beyond a single model at any given level. Determining the implications for reliability metrics at the system or subsystem level of a particular design using particular components in a particular configuration will require modeling up through several layers of the hierarchy. The general axiom of systems engineering applies: optimization for a quality (such as reliability) at a sublevel in a structural-functional hierarchy does not necessarily lead to optimization even for the analogous quality expressed at a higher level of system integration. Furthermore, the Army will have to optimize more than one quality (e.g., pulse reliability for at least two weeks of pulses, plus various mobility and lethality objectives). Optimization at lower levels for any one of the overall performance qualities may not provide the best system solution for all of them.

For all of these reasons, upward iterations through the hierarchy will be crucial. Similar reasoning applies to the downward flow of performance requirements (including reliability requirements) from the top level to the component level (and below that to the materials selection and materials design levels). High-level functional requirements may, on analysis at lower levels, turn out to be inherently incompatible (for example, they jointly "violate the laws of physics"). Or they may be jointly unachievable for all existing design options. In either case, some kind of "goal leveling" across performance requirements will be necessary. Additional downward iterations of different combinations of modified requirements will be necessary to make reasoned decisions about the "best" system trade-offs. For instance, lightening a vehicle by using advanced composite materials may increase its range per fuel load and may improve its pulse reliability, but these materials may require longer maintenance checks between pulses and, therefore, require additional maintenance specialists in the staging area to meet the fast refit requirement.

As the larger AAN process evolves with new combinations of tactics and doctrine, performance specifications will change (including the mission-specific metrics that define reliability requirements). Modeling the new options downward through the hierarchy-and running alternative solutions back up—will again be necessary.

Valid Data on Alternatives

Even in a well coupled hierarchical M&S environment, independent input variables must be set at each level. These include variables that specify design choices or environmental conditions specific to each level, as well as the input variables that represent design choices at the lowest model level in the overall simulation scheme. The utility and validity of a simulation exercise for making design decisions and system performance trade-offs depends on how accurately these input data characterize the design options and conditions that the simulation is supposed to represent. This simple point has important consequences for a simulation being used to assess a complex variable like AAN mission reliability.

When new design concepts are introduced at any level in the simulation hierarchy, the properties that influence the reliability metrics at that level may not be well characterized. New structural options may in principle be available for insertion into designs (for example, new materials that might be used in components and structures), but valid data on even well established properties that affect reliability may not be available to the designer. For AAN mission reliability to be analyzed objectively and reasonably, modelers will need sound data for all design options of potential interest and for all properties that significantly affect the reliability metrics at each model level.

Preserving Mission Reliability during System Trade-offs

Once RAMD is represented by measurable characteristics reflecting operational requirements in the system conception, design, and testing processes, the *fundamental systems engineering issue is whether all metrics representing these and other operational requirements can be met with known technology.* If all metrics cannot be satisfied in one system, trade-offs can be made to optimize the outcome. In the past, whether this was done systematically or haphazardly, RAMD values were often sacrificed for "performance" values, real or perceived. For AAN systems, *it may be necessary to sacrifice some desirable mobility, lethality, or survivability characteristics to maintain the level of AAN mission reliability required for an acceptable probability of success.*

A principal benefit of an M&S environment like the one proposed in Chapter 3 is that it allows the established trade-off methods of systems engineering to be applied to novel AAN systems, beginning very early with design conception and continuing, with increasing precision and certainty, through detailed design, engineering development, testing, and evaluation. With rigorous adherence to good systems engineering practices, a performance goal like mission reliability, which is a global property of overall system performance across a system's mission profile, can be achieved.

AAN mission reliability can only be assured if the trade-offs inherent in creating a novel and complex product that can be fielded by 2025 *maintain adequate levels of mission reliability.* Assume that an adequate M&S environment is available for a proposed AAN system concept. A reasonable starting point for designing the new concept is to attempt to meet all performance metrics (including those for reliability) with existing, well characterized solutions. Suppose, though, that all of the requirements *cannot be met jointly.* This is a likely outcome for the leap-ahead systems needed. The next step might be to look for less well characterized options that can be substituted for some of the tried-and-true standard materials, structures, and components. Because less is known about these options, additional physical testing of the proposed alternatives and modeling of the system configured with them will have to be done. Data on the alternatives must be validated, and additional *cycles of iterative simulation* will assess whether the new design can meet the requirements for mission reliability and other performance qualities.

Advances in materials engineering may be able to help here by providing new approaches to obtaining data about relatively untested options. For example, it is difficult to use accelerated testing methods to determine how a component fashioned by new means from novel materials of construction will respond to a complex duty cycle. Knowledge of the physical properties of the materials gained from experimental data, including their dynamic responses throughout the duty cycle, may make it possible to model the long-term failure, wear, and aging behavior of the alternative, in the context of a particular design for a particular system.

A radical form of this "search for better system inputs" is to look to materials engineering to provide a "new solution" that meets the particular requirements (e.g., specific strength or resistance to failure modes of the familiar options, or ease of replacement) of an element in the modeled system. "Designing" a new material (or novel structuring of known materials) depends, like the modeling of hard-to-test physical behavior, on knowing the physical properties that will provide the desired functional behavior and knowing how to engineer those properties into the structural element in question. These approaches will probably not be valid for the development of the first AAN systems, but they are discussed in the following section as longer term options for meeting the AAN functional requirements for reliability.

An equally valid approach from the standpoint of systems engineering is for designers to re-examine the performance requirements, including the reliability requirements, at each level in the M&S environment from the top down, to see if any can be relaxed without sacrificing the essential requirements for the system to do its job (i.e., top-down reduction of functional requirements). Eventually it may be necessary to compromise on functional requirements to find an acceptable system solution.

In the past, when a lower requirement for one performance goal was traded to achieve an acceptable metric for another, system reliability was often "traded away." To varying degrees, the justification for the other performance characteristic was considered "more important than cost," and decreased reliability could be compensated for by buying additional quantities of the system (for replacements). Two other reasons for sacrificing reliability have been, first, the lack of objective, assessable metrics for mission-specific reliability at each level in the structural-functional hierarchy of Army systems and, second, a dearth of hard data about the reliability-relevant properties of system elements that were introduced to meet other performance objectives. If reliability is considered on an equal basis with lethality, survivability, and mobility, then reliability can no longer be used as an excuse for poor design.

Even the best systems engineering in the world will not consistently produce AAN mission-reliable systems unless and until the following steps are taken to supplement systems engineering throughout the design, development, and testing process:

- Reliability must not be traded away to meet other performance objectives, at least not to the point that mission reliability will be threatened or lost.
- Designers must have a design construct (e.g., an M&S environment) for highly complex systems that incorporates meaningful, quantifiable characteristics that define mission reliability at the topmost system (platform) level and characteristics that are closely coupled with mission reliability at each lower level of the system structure-function hierarchy.
- Contractors who offer proposals to build a system, subsystem, or component should be evaluated (using the M&S environment) on the basis of the proposed design's capability to achieve the requirements for AAN mission reliability (as well as the requirements for other mission-critical system goals, such as system fuel efficiency [Chapter 4], vehicle mobility [Chapter 5], and precision engagement [Chapter 6]).
- Contracts should be awarded on the basis of meeting mission-specific reliability requirements, and contractors should be held to delivering what they promise. Source selection criteria must be changed to consider reliability on an equal basis with other mission-specific goals. Currently, reliability is often traded off for performance, which increases logistics support requirements for new systems.

THE THIRD APPROACH: RESEARCH TO ENABLE NEW RELIABILITY SOLUTIONS

Let us assume that the system design and trade-off analyses performed with M&S tools indicate that not all of the logistics reduction and performance requirements, including the reliability-related requirements, can be met jointly with materials, structures, and components that are well characterized from testing and accumulated experience in similar applications. An alternative to relaxing one or more requirements to optimize the system design is to search for better designs or for better components or materials. Although the better designs, components, and materials may not be ready for engineering and manufacturing development by 2010, the research to find them may be necessary to meet all of the AAN requirements at a later date. Furthermore, it is always possible that a breakthrough or burst of progress in a key area will lead to improvements sooner.

Improving System Reliability at the Level of Component Analysis and Design

Although much can be done in the near-term (by 2010) to improve existing M&S tools, research will be necessary in the following areas, even if the results do not bear directly on systems for AAN until after 2010.

- *mechanisms of failure* modeling, to relate structural failure modes at one level in the M&S hierarchy to physical properties at the next lower level
- *materials selection and materials design* to provide new options (and inputs at the level of component design and analysis) in the M&S hierarchical environment
- *prognostics* (the design and application of prognostic sensing technology) to monitor for physical precursors of failure when the mechanisms of failure for a design or a material are known but no better design or material (with respect to meeting all system performance objectives) is available

Modeling Mechanisms of Failure

Iterative simulation runs up and down an M&S hierarchy can only ensure system reliability to the extent that the models accurately represent the causal relations between the reliability-related characteristics (performance metrics) at one structural level and the physical properties at the next lower level of structure. Models can misrepresent these linkages in three ways:

- The models may be inaccurate because of errors in the assumptions or approximations used in the modeling tool itself or in the runs for a particular configuration.

- The models may be reasonably accurate around a "good design" point (anticipated range of operation and performance) but may not be able to predict off-design performance or identify failure signatures and failure modes.
- Data for accurate simulation of the system may be insufficient.

Improving the models to resolve these problems can be considered increasing their fidelity by incorporating more complete knowledge of the mechanisms of failure into the model.

When a system fails to operate properly during its mission, a failure has occurred. "Mechanisms of failure" is just another name for the causal linkages between structure at one level and successful performance at the next higher level of integration. "Physics of failure," a term often used to describe the gathering and applying of knowledge of these causal linkages, originated in efforts to improve the reliability of electronic materials and structures. Thinking in terms of the *physics* of failures has been highly productive in semiconductor electronics because a great deal is known about how the physical structure of semiconducting materials produces the functional characteristics of the "component" electronic device at the next higher level of organization. Building on the success of the physics of failure approach, the Army is now implementing physics of failure studies to assess the reliability of electronic packaging concepts that are still at the design stage.

A fundamental constraint on a "physics of failure" approach to determining mechanisms of failure, a constraint that is not always clearly recognized (or stated), is that the ability to predict failure modes and failure events from underlying physical properties depends on two factors. First, specific physical properties must be strongly linked to specific failures (for example, is occurrence of condition *A* sufficient in itself to cause failure mode *F,* or is it just a contributing factor that requires other conditions before *F* occurs?). Second, do we *understand* the causal structure that determines whether or not a failure will occur? As the causal relations between physical conditions and the occurrence of failure become more complex and our knowledge of that complexity becomes more tenuous, predicting failure modes and events becomes more and more speculative.

A more practical way to express this theoretical point is that research on the mechanisms of failure for AAN systems is unlikely to reveal *all* of the fundamental failure modes of a system and what causes them. In most cases, this is probably an impossible, or even a meaningless, task. However, to design and manufacture highly reliable components that can meet AAN performance requirements, enough must be known about the underlying properties and conditions that can create known or suspected failure modes (i.e., some of the causal linkages) to build components with superior performance in reliability-related characteristics.

An example far afield from the area of semiconductor design illustrates the potential value of modeling mechanisms of failure. Given the importance of energy management in reducing logistics burdens (see Chapter 4), many AAN vehicles or other systems will require high-horsepower engines that operate at high fuel efficiencies throughout the range of operating conditions required for AAN mission scenarios. These engines must also be highly reliable, not just when operated at "design" conditions but also under any conditions that occur during an AAN mission. Even if the engine is operated outside its design envelope for optimal performance, it must continue to perform, at least until a combat pulse has been completed and it can be returned to the staging area.

Designing this engine will require an understanding of some of the detailed physical characteristics of the engine's subsystems in relation to the performance of the entire engine. For example, the design engineer would want to know how the fuel-air mixing and combustion process is affected by local mixing inefficiencies, pressure oscillations in the fuel feed line, combustion instability in the combustor, soot formation and resulting inhibition of the ignition system, and the stability of lean flames, including local extinction and reignition. In each of these areas, knowing something about the conditions that can lower operating efficiency or damage the engine structures over time would help in modeling the mechanisms of failure for the high-efficiency, high-power, highly reliable engine the designer is trying to build.

If the designer has a simulation model that incorporates this knowledge of failure mechanisms, the model will be better at simulating how a real engine would perform under a broader range of conditions than a model that represents only the optimum design point of operation. However, the designer is never going to sit down with a set of fundamental physical equations (even a very large set) and "deduce" an engine design from them. Nevertheless, a simulation model that incorporates "first-principles" parametric representations for even some of the physical processes in an engine is likely to show the designer some unexpected failure modes when the model is run under off-design or nonoptimal conditions. But even a completely accurate physical description of the engine will not enable the designer to deduce all of the failure modes of the engine.

As the example of engine operating efficiency illustrates, much of the research that is often described as investigating "physics of failure"—that is, investigating the mechanisms of failure—can and should be part of research on the physical processes underlying the complex technologies needed for AAN systems, such as advanced engines, active suspension systems, and lightweight protection systems. However, the duty cycles for many commercial applications for these technologies will be very different from the duty cycles in AAN systems. Therefore, *the Army may have to support and encourage basic research on the broad issues in the mechanisms of failure that are unique to the duty cycles for AAN concepts of operations.* Two broad issues are (1) the relationship between dynamic physical conditions and properties (conditions and properties that do not vary uniformly over time) and failure modes of subsystems and components, and (2) how failure modes are affected by materials with different structural patterns at different spatial scales (ranging from atomic to micron scale), as opposed to materials with bulk properties determined predominantly by their atomic-scale structure.

Materials Selection for Improved Reliability

If all of the performance requirements, including the reliability metrics, for component-level models of an AAN system cannot be met with standard materials, seeking new materials is an alternative to relaxing the requirements. Appendix C, Materials Selection and Design, discusses how materials science and engineering can develop solutions for component design and analysis. Alternatives may exist among lesser known materials, and better materials databases and selection charts can help designers find potential solutions. Often these materials may require testing to determine how well they meet design requirements.

As materials science develops better tools for modeling the performance characteristics of materials based on their underlying structures, and as methods for forming materials with novel structures, particularly at very fine scales, are improved, an even more innovative approach may become possible. *The component designer may be able to call on the materials designer to design a new material to meet the performance requirements for a particularly demanding application.* The M&S tools needed to support "materials by design" must have the same generic capabilities as the tools at various levels in the M&S hierarchy for systems design. In fact, the M&S tools for materials design and processing can be considered another level of structure-function relationships below the component level. The extensions of current capabilities required to develop AAN systems will also be necessary at this new level in the hierarchy.

Prognostics

Prognostics (prognostic sensing technology) can be described as the use of sensor technology to detect precursors of failure before the failure occurs. Prognostics applies our limited knowledge of the mechanisms of failure to detect "failures in the making" so that the failure can be prevented, avoided, or ameliorated (the graceful degradation of performance).

If the M&S capability at each level in the hierarchy, including the just-emerging "materials design" level, could simulate physical reality and predict failure modes and events perfectly (i.e., if the mechanisms of failure linking each structure-function level to the ones above and below it were fully understood and had been incorporated into the models at every level) and if engineers knew how to design each level of a system so that all failure-causing conditions could be avoided, then prognostics would not be needed. Often, though, something is known about conditions that cause operational failures but not enough to ensure that none of them occurs. In some cases, an optimal design for the full set of performance requirements for a given system, subsystem, or component is known to be subject to a particular failure mode when certain antecedent conditions arise. In these cases, prognostic sensing technology can improve the reliability of the system.

The use of prognostic sensors is well established at the higher levels in the hierarchy of systems design. A warning light goes on when the lining of an automobile brake is worn to the point that a replacement is needed to avoid brake failure. An oil pressure gauge is not used by a knowledgeable driver or mechanic as a means to measure oil pressure but as a prognostic sensor indicating a condition that could lead to the catastrophic failure of the vehicle (oil pump wear or failure, a system leak, or overheating). The more innovative (and sometimes controversial) uses of prognostic sensing are for detecting precursors of structural failures at small spatial scales, particularly by sensors embedded in the material.

These new technological possibilities for small-scale sensors (measured in micrometers or even nanometers) to detect equally small causal preconditions for a structural failure have the potential to operate at the material and component levels of complex structures in a manner analogous to the more familiar prognostic sensors at higher, larger scales. The following general principles apply to prognostics at any level of system design:

- Using a sensor system for prognostics implies that something is known about the mechanisms of failure for the performance characteristic that the sensor is monitoring.
- If one knows enough about the failure mode and knows a way to avoid it, it is better to design the system not to fail rather than to use a sensor to predict when the failure will occur. If we do not know for sure how to avoid it and the failure mode is important enough, a prognostic sensor may be useful.
- Not every precondition for failure that can be monitored with a sensor is worth monitoring.
- Prognostic sensors are useful when the causal link between the precondition and the consequence is well established, the consequence is likely to lead to overall operational failure of the larger system, and *something useful and relatively easy can be done to prevent the operational failure of the larger system.*

Prognostic sensors could be used to speed the refitting of AAN systems between combat pulses. For example, knowing that an embedded sensor would detect nascent crack formation in a key structural component could be a faster way to ensure that a system is pulse-reliable than performing a laborious, and possibly destructive, testing procedure during each maintenance check. A prognostic sensor might contribute to pulse reliability by warning a well trained driver to avoid certain stresses, thereby trading a constraint on vehicle operation (a small degradation in performance) for a larger system failure. Although prognostics is not a substitute for AAN mission reliability, it is clearly a complementary technology.

SCIENCE AND TECHNOLOGY INITIATIVES TO ACHIEVE AAN MISSION RELIABILITY

Based on the preceding analyses of the role of reliability (and related concepts, such as maintainability, availability, and durability) in reducing logistics burdens for AAN systems and the technological opportunities for improving reliability, the committee concluded that the Army should pursue the following areas of scientific research and technology development. The order of a numbered item reflects a rough order of priority.

AAN Mission Reliability

Defining AAN Mission Reliability. Reliability for AAN systems (or RAMD for AAN) must be defined in relation to AAN operational concepts, as illustrated in this chapter by the examples of pulse-reliable systems and the improved maintainability required for rapid refitting of a battle force between combat pulses. Additional aspects of AAN mission reliability can be defined as the operational concept for the AAN evolves. However, the war-fighters and technologists must make every effort to define mission reliability in objective, quantifiable, and accountable terms. In short, the terms must be *usable* in system design and trade-off processes. Working definitions of mission reliability must begin at the highest levels of small unit and force-on-force engagement analysis and proceed down to the reliability requirements for individual systems (e.g., AAN combat vehicles). Factoring reliability into the logistics analyses necessary to design, develop, and field systems that will meet AAN performance objectives by 2025 will require clearly linking reliability requirements to mission performance. The higher-level, functional definitions of reliability should be reviewed and updated by both war-fighters and technologists as the concepts of AAN operations evolve. The science and technology community should ensure that the lower levels of system analysis include reliability-related performance metrics that contribute to reliability at the next higher level of system integration.

Three Approaches to Mission Reliability

1. **Designing for Reliability with a Distributed M&S Environment.** Five extensions of current capabilities and design approaches must be incorporated into M&S tools at every level of system structure, from components to fully integrated systems. These extensions are (1) models incorporated into the M&S environment that can represent the system properties and environmental conditions that affect AAN mission reliability requirements, (2) measurable reliability-related requirements defined for the models at each level in the M&S hierarchy, (3) iterative simulations up and down the hierarchy of models in the design and engineering process, (4) provisions for obtaining valid data on lesser known design options that could contribute to satisfying combinations of AAN performance goals (including the goal of mission reliability), and (5) mission reliability, defined by assessable reliability requirements, as a performance objective for design and engineering development that cannot be compromised to meet other performance objectives.
2. **System Trade-offs That Include Reliability as a Primary Performance Goal.** The M&S environment used for designing reliability into systems can also enable rational trade-offs when existing technologies and design concepts do not meet all of the primary performance goals. Especially in the near-term, compromises will be necessary, and optimum system performance should take priority over meeting individual performance goals or the performance of a subsystem. If objective, measurable reliability requirements have been defined for the system at each level in the M&S environment, then adjustments to those requirements should flow down the hierarchy, and the consequences of other design changes on reliability should be assessed upward through the hierarchy. Novel or less conventional technological or design alternatives should be evaluated in terms of their impact on reliability, as well as on other performance goals. Contractor proposals should be evaluated, and contracts awarded, on the basis of how well they meet reliability requirements, as well as other performance goals.

3. **Application of Materials Science to New Reliability Solutions.** Although the payoffs are likely to come after the 2010 deadline for decisions on major AAN systems, several important areas of basic research are likely to provide important contributions to developing systems that can meet AAN reliability requirements, as well as other primary performance requirements. The Army should continue to leverage its resources in these areas of research through networking with industry and academic partners and through active participation in joint programs. Three research areas that are particularly important for improving reliability are (1) investigating mechanisms of failure and incorporating this knowledge into M&S tools, (2) selecting or designing alternatives for materials that can meet AAN requirements, including reliability requirements, that familiar materials cannot meet, and (3) using embedded prognostic sensing technology in designing structures and components. The potential impact of this research—and a realistic assessment of their potential contributions to AAN solutions—should be framed in terms of refining, improving, and extending to smaller spatial scales the hierarchical M&S environment for systems design and logistics trade-off analyses.

8

Soldier Sustainment

The Chief of Staff of the Army has stated that "Soldiers are our credentials." The committee strongly endorses this credo and believes it will still be true in 2025. No matter how many tons of ammunition and fuel are available in the battle area, soldiers must be present to use them. Therefore, sustaining the soldier is the *sine qua non* of any logistics systems.

The soldier sustainment logistics burden is not measured in tons but in necessity. If soldiers cannot sustain themselves, the battle will come to a halt and be lost. Therefore, the committee believes that the soldier's logistics load should be reduced and that every effort should be made to enable soldiers to conduct continuous operations with minimum personal resupply.

Reducing the soldier's load will require improvements in compact electric power, lightweight protective garments and ballistic protection, nutrition and medicine, food and water production and delivery, and other technology areas. Reducing the soldier's logistics burden will increase fighting effectiveness and will ultimately reduce the number of soldiers needed to accomplish any given mission.

COMPACT POWER

The combat soldier will become increasingly dependent on portable electronic systems, and the provision of adequate power for dismounted soldiers is a major logistics consideration. Research objectives and relevant technologies for improving energy sources and electronics were reviewed in a 1997 NRC report, *Energy-Efficient Technologies for the Dismounted Soldier* (NRC, 1997a).

The committee is aware of several technological developments that may ultimately reduce the weight burden associated with energy needs for the individual soldier in the AAN time frame. One of these is rechargeable fuel cells, which were discussed in Chapter 4. Dramatic increases in stored energy will require that the Army move away from traditional electrochemical batteries toward nontraditional energy storage concepts, such as microturbines and nuclear "batteries," which are discussed below.

Microturbines

The compact gas turbine, which uses hydrogen as its primary fuel source, appears to be an appropriate area of investigation for AAN, and the Army has sponsored significant research in microturbines (NRC, 1997a). However, these power systems will still have to meet the same requirements as large power systems in terms of their capacity to produce net electrical power. Because the capability of a turbine power plant to provide net power output is a function of the pressure ratio, turbine efficiency, compressor efficiency, and maximum temperature at turbine inlet, the characteristics of these new devices will have to be assessed to determine if they meet the requirements. Efficiencies of aerodynamic compression and expansion devices decrease as surface-to-volume ratios increase, so mechanical, compressor, and turbine efficiencies will have to be high enough to provide enough net power output to drive the power generator. The overall efficiency of the power plant may not matter as long as the machine is capable of providing enough net power. (Limitations on using hydrogen, instead of JP-8, as a battlefield fuel are discussed in Chapter 4.)

Nuclear "Batteries"

One way to minimize the weight burden of batteries for the individual soldier would be to develop radioisotope-based power sources to replace small batteries. Commercial, radioactive energy sources are already found in smoke detectors and some wrist watches with luminous dials. One of several means of converting isotope power to electric output is thermoelectric (TE) conversion (utilizing the heat generated by isotopes). Some DARPA projects are focused on increasing the performance of TE junctions by an order of magnitude, which would greatly improve heat-to-electric power conversion efficiency. Past experiments have shown that the direct conversion of nuclear to electric power by bombarding silicon "solar" cells with low level nuclear particles is feasible (Aslange and Emin, 1997). Unfortunately, the life of silicon cells under these conditions is extremely limited because of atomic lattice damage. Researchers at the University of New Mexico and Sandia National Laboratories have presented data suggesting that alternate semiconductor materials, the so-called icosohedral borides (e.g., $B_{12}P_2$ or $B_{12}As_2$), may be "self-healing" under low-level nuclear bombardment and might be more feasible for battery-like nuclear-to-electric power converters (Aslange and Emin, 1997). DARPA has recently initiated an experimental feasibility study of this concept. Because of the low levels of radiation associated with the gamma radiation of the power source, typically 40 keV, shielding would have to be the equivalent of lead foil. A nuclear battery would be a lightweight, "eternal" power source. These technologies would be most beneficial for low-power batteries for individual soldiers and for remote sensors.

PROTECTION OF PERSONNEL

In a general sense, the functional requirements for body armor are the same as those for vehicle armor. The objective is to increase protection per unit of mass or volume. Lightweight building blocks for body armor for combination systems particularly polymer and ceramic composites, look promising. Unlike vehicle armor, however, body armor must be flexible enough so it does not interfere with the mobility and effectiveness of the soldier. A "lightweight" armor on a 15-ton vehicle is likely to be much too heavy for a 180-pound soldier who is already carrying a combat load.

Body Armor

Traditional designs for body armor restrict mobility and can significantly limit a soldier's performance. This is mainly because conventional armor systems (such as steels, aluminum alloys, ceramics, and monolithic reinforced polymers) are clumsy and heavy. In bulletproof vests, for example, hard ceramic provides an impact-resistant surface, but the vest is large and may not conform to the contours of the body. Even relatively light vests constructed of woven polymeric composites (including Kevlar and spectra fibers) can be uncomfortable to wear in hot weather. An ideal armor system would be lightweight, flexible, and easy to manufacture.

Two technological challenges for body armor are weight and practicality. These may be overcome by using a segmented design for the armor system, for example, ceramic plates supported by energy-absorbing woven polymer backing. Polymer materials that mimic spider silk, mollusk shells, and other natural materials could also be used as building blocks for lightweight body armor to reduce the vulnerability of limbs to bullets and shrapnel. Body armor systems could be equipped with sensors and detectors that monitor body functions in case of a hit and assess the degree of injury. These could be in-situ sensors (e.g., piezoelectric polymers that sense mechanical changes and detect electrical signals) that are part of the composite armor material. The body armor systems may also be combined into protective garments providing protection from chemical and biological agents and nuclear radiation.

Research in the area of polymers for personnel protection, especially on new fiber technologies and biomimetic (protein-based) polymers, could lead to important building blocks for body armor, such as filaments, cloth, or matrix materials that could be filled with ceramic powders. Other building blocks for body armor include microlayered composites (such as ceramic-metal, ceramic-polymer), gradient materials with hard coatings (such as carbonitrides), and hybrid materials with smart properties.

Active Protection Systems

In the AAN time frame, it may be feasible to develop active protection systems for soldiers using technologies and techniques developed for active protection systems for vehicles (see Appendix D). When sensors detect a projectile threat, a smart defeat or energy-absorbing system could be activated to increase the soldier's survivability.

MEDICINE AND NUTRITION

The soldier in the AAN will have complete SA of his position, the location of his unit and other friendly forces, and the location of enemy forces. Similarly, each unit will have SA of the individual soldier—his location, how much ammunition he has, how much water and food he has, and his state of health. The Navy already has a system under development for transmitting medical information. The system is a vest with a grid of fibers. When a group of fibers is torn by a projectile, the location and the extent of the wound (as well as the location of the sailor) are transmitted to a central location where medical personnel perform triage. Because medical support on the battlefield will be minimal, the decision of whether or not first aid is required will be critical.

Up to now, the Army has had limited success with exoskeleton arrays. However, as new sensors and controls and new materials are developed, the Army may decide to reevaluate these areas. It is certainly well within the Army's research and development capability to develop a medical patch through which wounded soldiers could receive blood coagulants, pain killers, and other medicines. Uniforms, boots, and gloves could be structured to serve as splints for broken bones. With telemedicine, diagnoses can be made from outside the battle areas and enable minimally trained soldiers to perform lifesaving procedures.

The space program could be a model for sustaining soldiers in AAN combat scenarios. Astronauts can function for long periods of time without resupply. "Toothpaste tube meals," for example, already weigh less than the predicated combat ration weight of 0.8 pounds per meal. By 2025, a nutrient patch could be developed that would minimize the requirement for bulky food rations. Astronauts also recycle urine, which reduces the need for an external water supply. Pills could be developed to improve the soldier's performance in combat. To paraphrase the motto of DuPont, we would have "better soldiering through chemistry." One pill might enable an individual to operate effectively for 24 hours a day while another might increase visual acuity or hearing. Pills might also enhance physical and cognitive abilities or reduce susceptibility to biological and chemical attacks.

OTHER TECHNOLOGIES

Research in several other areas important to AAN soldier logistics has been promising but has progressed slowly and has not received significant support. Some of the potential benefits are described below.

Lightweight protective garments could reduce the weight of current chemical protective garments from 15 lbs. to 6 lbs., possibly even 3 lbs. Army planners should also carefully consider the benefits of thermal management. Cooling the soldier ensemble could significantly reduce the need for large quantities of water in arid areas. The current overgarment for thermal management weighs 15 lbs. and uses 200W of electricity for three hours. Improved protective garments could weigh 6 lbs. and use 300W for 12 hours or more.

The weight of rations for an AAN battle force of 8,000 soldiers deployed for 14 days would be about 135 tons, which is only a small fraction of the total deployment weight. Improved ready-to-eat meals (MREs) could reduce the weight of combat rations carried by the individual soldier from 1.5 lbs. to 0.8 lbs.

Current DoD planning for portable water consumption is 20 gallons per soldier per day, with 3.9 to 7.7 gallons for drinking, personal hygiene, field feeding, and treatment for heat injury. Water weighs 8.34 lbs. per gallon. In high temperature areas, as many as 200,000 gallons, weighing approximately 650 tons will be required per day for the AAN battle force. The total water requirement for a 14-day deployment would weigh more than 9,000 tons. In contrast to food rations, this is a significant fraction of total deployment weight. Therefore, developing storage, distribution, quality control, and treatment technologies for water will be essential. Rapid bioremediation of nonpotable water sources could be available by 2025. In addition, AAN concept developers should address questions of water usage and reassess their assumptions about the amount of bottled water to be supplied.

Current capabilities for field feeding include burner units, containerized kitchens, and flameless ration heaters. The capabilities that will be necessary for AAN are on-demand feeding, automated ration dispensing, self-heated rations, and self-chilled beverages. If AAN soldiers could subsist solely on combat rations, these technology and support requirements would be reduced considerably.

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The individual soldier will be the single most essential combat system in the AAN. As part of a battle force with minimal logistical support, technologies will have to extend the soldier's range and duration of self-sustained operations. Reducing soldier logistics will have a multiplier effect of increasing combat effectiveness and reducing logistics burdens for medical support, water, and food.

Because individual soldier logistics are an essential part of AAN, the Army should consider establishing a science and technology objective (STO) to focus on technologies to extend the range of self-sustained soldier performance to distances and durations that would enhance AAN operations. The STO would adapt M&S tools to analyze and determine objectives for the soldier as a system that would both reduce logistics demand and increase combat effectiveness.

Although it may appear that the potential for reducing soldier logistics is small in comparison to reducing the logistics burdens for fuel or ammunition, the committee believes that soldier logistics deserve special attention and that research and technology development for AAN soldier sustainment should be treated in a separate context. The Army's Soldier System Command (or successor organization) that is now responsible for development of soldier systems, should be expanded to include management, funding, and trade-off analyses for the AAN soldier.

9

Joint Force Research and Development

This chapter discusses research and development that is not within the Army's exclusive purview. This research, which should be conducted by the other services or under joint auspices, includes the development of strategic lift capabilities, long-range supporting fire, and interoperable command and control systems.

STRATEGIC LIFT CAPABILITIES

The AAN concept is founded on the ability of an AAN battle force to be deployed from the continental United States to a forward base area within 1,000 km of the mission area. Deployment from the United States to a staging area will require that Army assets be transported by either the Air Force or the Navy or a combination of the two. The committee found little DoD or service research focused on upgrading the current strategic lift capability, which is limited by payload in the air and ship speed on the sea. The Army has not stated requirements for heavy (> 500 tons) airlift or fast (> 100 knots) sealift although research is under way in the civilian sector. The Army, based on what it learns in the AAN process, should evaluate the need for such capabilities.

The Air Force plans to improve its C-17 advanced military airlift aircraft as it extends the lifespan of the fleet. The C-17 can transport more than 85 tons and has a cruising speed of Mach 0.74 to Mach 0.77. The C-17's range is more than 4,000 km, and the plane can land in less than 3,000 feet. In fact, the C-17 holds a world record for taking off in 417 meters with a cargo of more than 22 tons and landing in 413 meters. (Boeing, 1998) The number of C-17's planned in the inventory, however, will not be adequate to meet the AAN requirement of strategically airlifting 1,000 to 2,000 15-ton vehicles, up to 8,000 troops, and their accompanying supplies in a 48-hour time frame (see Chapter 5).

For the foreseeable future, the only military capabilities for strategic sealift are the fast sealift ship and the large, medium-speed, roll-on/roll-off (LMSR) ship. The fast sealift ship, with limited roll-on/roll-off capability, moves at 30 knots and displaces 61,500 tons (USN, 1998). The newer LMSR displaces 62,700 tons and moves at a speed of 24 knots. It can carry 58 tanks, 48 other tracked vehicles, and more than 900 trucks or other wheeled vehicles (DoD, 1998b). An AAN support sealift must be able to carry much larger loads and travel at speeds of more than 100 knots.

Research being conducted by industry to improve both sea and airlift capabilities has been limited by a lack of clients who are willing to support development. Industry personnel contacted by the committee believe that the concepts of both heavy airlift and fast sealift have been validated and that there are a few commercial applications for them. But the number of commercial applications is too small to justify the commercial investment, and a partnership arrangement will be necessary to make development cost feasible for both the military and commercial market.

Professor Charles Owen at the Illinois Institute of Technology proposed a design for a lighter-than-air carrier that could carry 3,500 passengers and 35,000 tons of cargo (Nadis, 1997). Unfortunately, this carrier would have a limited air speed and be subject to the same constraints that face all lighter-than-air carriers. For AAN, the Army requirement is to carry a nominal 500 tons at speeds slower than a C-130 but faster than a lighter-than-air vehicle.

Other revolutionary proposals have also been made. Lockheed-Martin, for example, has investigated placing floats on the C-130, which would give the C-130 the capability of linking up with prepositioned floating logistics supplies and delivering them to a battle area rapidly (Donaldson, 1997). Depending on the geography and enemy situation in the battle area, C-130 aircraft could be used for either operational or strategic lift.

Domestic and international commercial shipping interests are working on the development of high-speed ships. Both Russia and the United States have design projects for ships that can carry as much as 10,000 tons at a speed of more than 100 knots with ranges of more than 10,000 nautical miles. These ships could be used to transport personnel and supplies from a floating depot or from the continental United States (Donaldson, 1997).

Heavy lift aircraft and fast ships also have considerable commercial potential. Air transport or fast sea transport of high value commodities would substantially reduce a manufacturer's inventory. Even if commercial aircraft and ships are available by 2025, they will probably not have the unique characteristics required by the military. Now is the time for the Army to begin working with the Navy and the Air Force to ensure that commercial developments take military requirements into account. This intervention could involve partnerships and/or arrangements similar to the current Civilian Reserve Air Fleet (CRAF) program. Under CRAF, civilian air carriers are committed to providing passenger and cargo capacity for the military when necessary in exchange for government airlift business in peacetime (Rutherford, 1995).

This approach would be in keeping with the recommendations in the *STAR 21* study (NRC, 1993a) concerning more conventional lift capabilities. The study stated:

> The STAR Committee suggests that CRAF is a resource the Army can exploit more fully in the future. To do so the Army should go beyond passively "making do" with whatever capacity comes out of current or future CRAF arrangements.
> The Army should work actively to influence CRAF capabilities. Such influence can be exerted in two ways: (1) by persuasion of the parties involved (i.e., the commercial cargo carriers) and (2) by seeking legislative inducements that favor capabilities the Army will need.
> (NRC, 1993a)

This strategy is more urgently needed now than it was when the *STAR 21* study was completed in 1993 for two reasons. First, advances in technology have made possible greater lift capability than was imagined in 1993; second, the AAN concept requires rapid deployment of a lighter force. Air carriers are more likely to be able to move a light force than large numbers of 70-ton tanks.

In addition to lifting the force to a staging area by air, the Air Force may also be called upon to resupply the battle force by parachute drop. The focus areas for research are advanced parachutes, nonparachute decelerators, precision airdrop, and high-performance computing. These technologies could move the AAN from "just-in-case capability," through "just-in-time capability," to "precision resupply" capability.

LONG-RANGE SUPPORTING FIRE

The AAN battle force will have both battlefield mobility and battlefield lethality. The first can require only Army capabilities, but the second will certainly require support from the other services. As the Army has moved forward to define its AAN concepts for 2025, the other services have focused more on the intermediate time frame, 2010 to 2015.

Major concepts of *Joint Vision 2010* are focused on "dominant maneuver" and "precision engagement" (see Figure 9-1). Both concepts involve using all components of the U.S. military across the selected battle space. Dominant maneuver is the "application of information, engagement, and mobility capabilities to position and employ widely dispersed joint air, land, sea, and space forces to accomplish assigned operational tasks." Precision engagement is "a system of systems that enables...forces to locate the objective or target, provide responsive command and control, [and] generate the desired effect. . . " These two concepts are coupled with focused logistics and "full-dimensional protection," the multiservice capability to control the battle space both horizontally and vertically. In short, future military operations will require the integrated capabilities of all of the services.

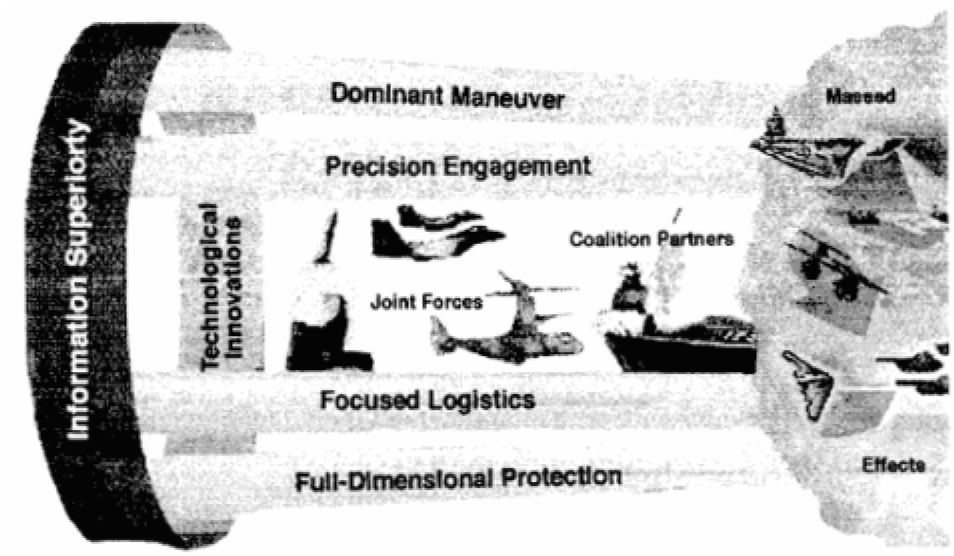

Figure 9-1
Joint Vision 2010 operational concepts. Source: DoD, 1996.

As the Army continues to develop the AAN battle force concept, it must work closely with the other services and DoD to determine which battle force needs should and would be met by other services. Every precision round launched by another service is a round that does not have to be carried to the battle area by the battle force. A combination of fire support by other services and extended-range fire support by Army units operating from the staging area could substantially reduce the logistics requirements of the battle force.

INTEROPERABLE COMMAND AND CONTROL SYSTEMS

The success or failure of the AAN concept may well depend on its C4ISR (command, control, communications, computing, intelligence, surveillance and reconnaissance) capabilities. The four main concepts of *Joint Vision 2010* assume an envelope of "information superiority," which will require linkage and integration with systems of other services. Although the Army should proceed to develop C4ISR capabilities for the AAN battle force, these capabilities should be part of the collective joint information superiority. Every capability that can be provided to the Army by another service operating under the concepts of *Joint Vision 2010* reduces the need for the battle force to carry equipment and personnel into the battle area. Focusing on joint responsibilities not only can increase the combat effectiveness, but also can reduce the logistics burden of the AAN battle force.

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The Army will depend on the Air Force and Navy to ferry the battle force and sustaining supplies to the staging area, to provide coordinated fire support, and to assist with C4ISR. It is also likely that much of the operational mobility requirement will be satisfied by the Air Force. It is imperative that the Army participate in planning for this support to ensure that operational and logistical needs of the AAN battle force can be fulfilled.

Technology developments necessary to enable strategic lift of the AAN battle force will probably overlap with technology requirements for operational, and possibly tactical, mobility. The Army should identify the overlapping requirements and encourage DoD to establish responsibilities among the services for satisfying these requirements as soon as possible.

10

Investment Strategy for Research and Technology Development

This chapter provides a road map for achieving future combat systems with reduced logistics support requirements. It describes the central role played by defense research and development programs in advancing U.S. technology and summarizes the target areas for research and technology development discussed in Chapters 3 through 9. Each of the target areas is related to reduction goals for specific logistics burdens and to associated road map objectives for AAN research and technology development. Overall, the chapter outlines an investment strategy for achieving AAN capabilities and significantly reducing logistics demand.

ROLE OF DEFENSE RESEARCH AND DEVELOPMENT

The political and economic context of DoD's basic research has changed dramatically. Industrial competition has become global, and the commercial market has become much larger than the military market. These changes have had several implications for defense-related research and development. First, the commercial sector is driving many, if not most, of the near-term advances in components and systems. Second, DoD must incorporate commercial products into defense systems, adding ruggedness and military specialization as an overlay, rather than developing military-specific components. Third, international competition and the desire for near-term profits have reduced longer-term investments by industry in many areas of basic and applied research.

Figure 10-1 shows how these changes have affected one specific area, semiconductor integrated circuits (IC), which are a critical aspect of the information dominance and near-perfect SA on which the AAN is predicated. Similar examples could be cited in other technology areas, such as wireless communications and turbine engines. In 1976, U.S. military purchases accounted for 17 percent of IC sales worldwide ($700 million out of total sales of $4.2 billion)—a significant market share that gave DoD leverage in defining product specifications and directions. In the next 20 years, the U.S. military market increased only marginally, to $1.1 billion, while the commercial market exploded to $160 billion (ICEC, 1998). The military market now accounts for less than 1 percent of sales, and the commercial market has become the dominant force in setting IC product directions. Although lower prices have resulted, the DoD is now compelled to use commercial IC products and adapt them to meet military requirements, as necessary.

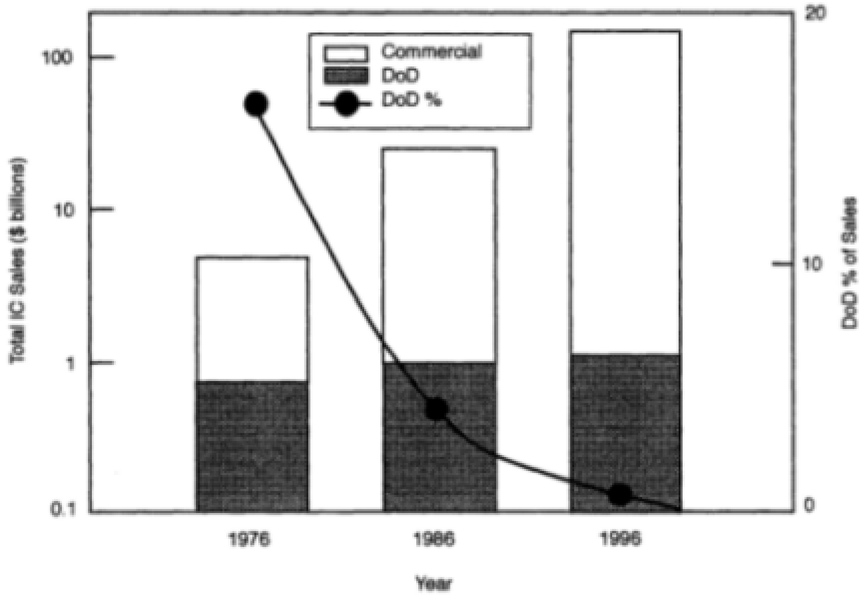

Figure 10-1
DoD's decreasing share of the market for integrated circuits. From 1976 to 1996, the percentage of sales to DoD decreased from 17 percent to less than 1 percent of the market. (ICEC, 1998).

At the same time, competitive pressures have shortened industry's development horizons to one or two product cycles. As former director of defense research and engineering, Dr. Anita K. Jones, has observed, ". . . industry research and development horizons are increasingly near-term." The horizon for the information technology industry sector, for example, is typically three years or less (Signal, 1997). In a cycle that begins with S&T (science and technology) and runs through development and production to life-cycle support, DoD has little to gain by adding a few additional dollars to industry's profit-driven, near-term development. Except for requirements that are truly unique to defense applications, DoD can exert much more influence by leveraging its dollars either at the front end in the enabling S&T phase or at the back end by adapting commercial technology to meet DoD needs.

Nevertheless, commercial industry remains dependent on the federal government for investments in long-term, higher risk S&T research. Historically, DoD has provided 15 to 20 percent of the total federal investment. In fiscal year 1997, expenditures by all of the services accounted for almost $8 billion in basic and applied research and advanced technology development (Touhy, 1998). This amount represents 40 percent of federal spending for basic research and includes more than 70 percent of all federal investment in microelectronics and electrical engineering (Signal, 1997).

U.S. industry has become increasingly dependent on the crucial leverage of government-funded research conducted at universities and in federal laboratories.

Although DoD's research investment has declined in constant dollars, the percentage of the DoD budget has remained stable since World War II because the relationship with industry has served the needs of the DoD, the research community, and the commercial sector. The imperatives of national defense have enabled DoD to invest directly in important new ideas with adequate resources to make a difference. Although this focused approach has not led to success in every project, it has led to enough successes to foster enormous progress in new technologies for both the military and commercial sectors. Early-stage development of new technologies is almost always applicable to both sectors. Therefore, by investing wisely, DoD can influence the directions of research and guarantee an adequate research base for technologies to meet its future needs.

DoD can also leverage its investments by coordinating teams drawn from federal laboratories, industry, and universities for demonstration projects to develop new defense applications based as much as possible on commercially available components and software. The S&T advantage of U.S. forces will increasingly depend on adaptations of commercial products with a defense overlay, rather than on expensive military-specific designs.

ARMY SCIENCE AND TECHNOLOGY PROGRAM

Army and DoD S&T programs include basic research (budget line item 6.1), which increases scientific understanding, applied research (budget line item 6.2), which identifies and exploits technology opportunities based on new knowledge and evaluates their technical feasibility to increase war-fighting capabilities, and advanced technology development (budget line item 6.3), which demonstrates applications to specific military systems, to speed the transition to maturity and insertion.

The Army share of DoD funding for research in all three categories is shown in Figure 10-2. Like overall DoD investments, funding for research has remained a constant

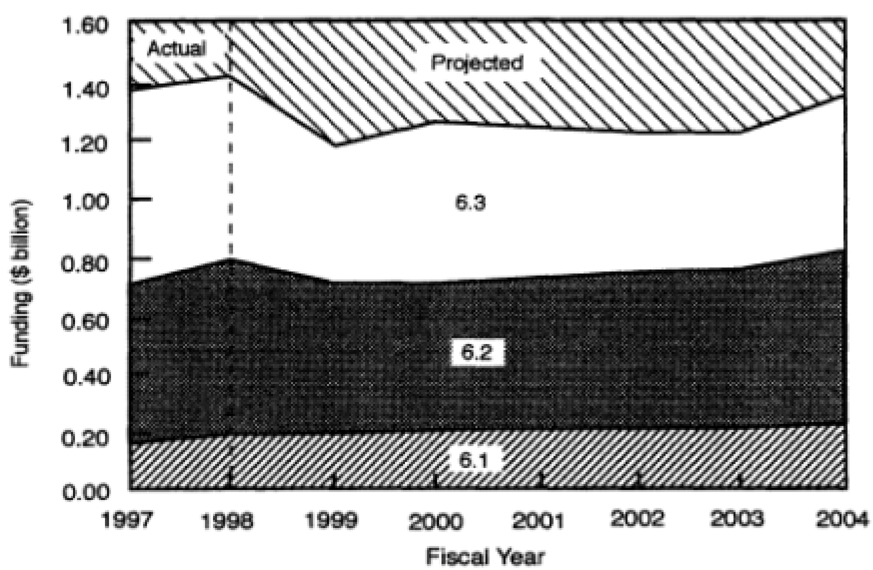

Figure 10-2
Army funding for research. Source: DA, 1998.

proportion of Army appropriations, although investment in constant real dollars has declined steadily since the end of the Cold War along with the rest of the defense budget.

The research and technology development needed for the AAN will require a cooperative effort. As the Army has fewer and fewer dollars to invest, it will become increasingly important for the Army to leverage the research activities of industry, government, and the other services. Army dollars should be invested principally in projects that will meet Army-specific requirements or that will be undertaken only if they are funded by the Army.

Strategic Research Objectives and S&T Objectives

The Army and DoD use the term "Strategic Research Objective" (SRO) to refer to an area of scientific research selected for emphasis because of its potential relevance to military operations, particularly for long-range, high payoff applications. The initial DoD SROs originated as Army SROs and are described in Box 10-1.

The relatively small number of Army (and DoD) SROs should not be confused with the roughly 200 Army Science and Technology Objectives (STOs). An STO states a specific, measurable technology advance funded by applied research or exploratory development dollars (budget line items 6.2 or 6.3) and is to be achieved by a specific fiscal year. By contrast, Army SROs focus and guide the S&T community on predominantly basic research (budget line item 6.1) that can be linked, although more tentatively than an STO, to Army requirements for technology development (DA, 1997c).

Strategic Research Objectives and AAN Situational Awareness

Based on the critical role of the technologies for enabling the near-perfect SA required to achieve "one-round, one-target" lethality for the AAN, as well as other operational efficiencies, including terrain awareness, operational energy management, and just-right logistics support, the committee believes that the current SROs in nanoscience, mobile wireless communications, intelligent systems, and compact power have the potential to support logistics burden reduction. The research areas that should be given the most emphasis are discussed below.

Nanoscience

Appendix F describes how the historical trend of increasing computational power at decreasing cost (according to Moore's Law) has been based entirely on the integration of increasingly large numbers of metal-oxide-on-silicon semiconductor devices on a given area of silicon substrate. For this trend to continue beyond the presently perceived physical limits on decreasing the size of silicon-based transistors (e.g., approximately 50-nm gate widths for CMOS [complementary-metal oxide on silicon] devices), new device concepts and computing architectures will have to be invented. Decreasing the size of transistor devices below these physical limits is likely to involve quantum devices with scales on the order of electronic wave functions (1 to 10 nm) or devices based on Coulomb blockade effects.

Box 10-1 Army Strategic Research Objectives

Biomimetics. novel synthetic materials, processes, and sensors through advanced understanding and exploitation of the design principles found in nature

Nanoscience. innovative enhancements in the properties and performance of structures, materials, and devices that have controllable features on the nanoscale (tens of angstroms)

Smart Structures. advanced capabilities in modeling, predicting, controlling, and optimizing the dynamic responses of complex, multi-element, deformable structures used in vehicles and systems

Mobile Wireless Communications. rapid, secure transmissions of large quantities of multimedia communications

Intelligent Systems. systems that can sense, analyze, learn, adapt, and function in changing hostile environments

Compact Power Sources. improved batteries and fuel cells, as well as the identification of new concepts relating to energy density, operating characteristics, reliability, and safety of portable power

(DA, 1997c)

So far, no device has emerged as a clear competitor to conventional silicon technology, although alternatives do exist (e.g., gallium-nitride for wide-bandgap semiconductor applications). Also, decreasing the size of interconnections between the devices, referred to as packaging, will become as significant a challenge to engineers as decreasing the size of the individual devices.

Even if nanoscience does not lead the way to new paradigms for the fundamental elements of computing circuitry, it will have an impact on a wide range of sensor technologies. Especially important areas for research include (1) detectors for chemical and biological agents and (2) materials for focal plane arrays to detect and image electromagnetic radiation, particularly in the infrared region.

Mobile Wireless Communications

AAN SA will rely heavily on communications, and the Army urgently needs a total systems simulation of these communications needs, along the lines of a distributed M&S environment that can realistically simulate functionality under combat conditions. The engagement and system level simulations need to be linked to the protocols for available and projected hardware and software subsystems, so that modeling results can flow up and down the structural hierarchy. These simulations should be updated as experience is gained from Army XXI and as planning for the AAN continues.

An important SA issue that the Army must address for both Army XXI and the AAN is the communications burden of new sensor systems. Proliferation of sensor systems with high data-link requirements on platforms, such as UAVs or UGVs, located remotely from the point where the sensor information is used, will compete for available communications bandwidth with other essential communication functions, such as command and control. Sensor fusion and advanced signal processing on the remote platform will add complexity and cost to the individual sensor applications but may be essential for capacity and robustness of the overall C4ISR system.

Intelligent Systems and Compact Power

The intelligent systems SRO is directly applicable to autonomous vehicles as AAN sensor platforms and to automated subsystems to reduce AAN crew size and manage energy demands. AAN soldiers can be expected to play critical roles as sources, processors, and recipients of sensor data under battlefield conditions even more fluid than those anticipated for Army XXI. Compact power sources could reduce the logistics burden for the AAN battle force and increase the effectiveness of soldier systems. Combined with energy-efficient technologies in future soldier systems, research under the compact power SRO should lead to the development of compact power technologies that would simplify soldier-level logistics requirements (NRC, 1997a).

Strategic Research Objectives and Lightweight Materials

Two of the SROs, biomimetics and smart structures, could lead to the development of new and novel lightweight materials, but the time frame for incorporating the resulting innovations into fielded systems extends beyond the rapidly approaching date required for initial operational capability of AAN systems. If research is directed toward reducing weight and increasing reliability, the results could significantly reduce overall logistics burden. Some of the applicable materials research will be undertaken by the civilian sector in pursuit of commercial aims, but the impetus and direction for the development of military materials, especially new armor building blocks and architectures perhaps with joint-service participation. for incorporation into protective systems, must come from the Army,

Strategic Research Objectives for Logistics

The Army sponsor of this study asked the committee to identify candidate research topics for a new SRO that would focus on reducing logistics demand for the AAN. Representatives of the Army logistics community further suggested to the committee that an SRO dedicated to logistics technologies and incorporating research into areas such as "ultrareliable" systems, prognostics, or fuel efficiency might be an appropriate focus for basic research. However, the committee was asked to address technologies to reduce the logistics demands of AAN systems, not technologies to improve logistics operations.

Fuel economy and system reliability are important objectives for reducing logistics burdens, but the committee's analysis shows that they should be considered broad performance objectives of an entire system, and should be designed into AAN systems at every level of subsystem and component analysis (see Chapters 4 and 7), rather than as guides for research or S&T development. Prognostics could improve system maintainability, but the committee considers prognostics to be one of several components of the broader area of materials research and structural design that could improve the maintainability and reliability of AAN systems (Chapter 7).

During the course of the study, the Army proposed establishing a new SRO focused on designing new armor materials. The committee believes that advanced materials with lightweight, protective, high-performance characteristics will have to be available well before 2025 to be incorporated into AAN systems. Successful candidates *within that time frame* are, therefore, more likely to result from applied research and advanced development of known technologies, rather than from basic research. Whether or not the Army proceeds with an SRO in this area, which would be valuable in the long-term, the Army should focus on applied research and technology development that facilitates the integration of new materials into future system designs because of the importance of reducing weight to logistics savings.

INVESTMENTS TO REDUCE LOGISTICS SUPPORT REQUIREMENTS FOR AAN SYSTEMS

The preceding section described the research emphases of the Army's existing S&T program. This section describes areas of research and technology development that the committee recommends for investment because of their importance for reducing logistics support requirements for AAN systems.

Road Map Objectives

The committee derived road map objectives based on the burden reduction goals discussed in Chapter 2 from the technology assessments presented in Chapters 3 through 9. Whereas burden reduction goals are broad and can be pursued in various ways, the road map objectives require moving in the direction of reducing logistics demand. Through the technology assessments, the committee identified several areas of research or technology development as key enablers for achieving the road map objectives.

Table 10-1 lists the burden reduction goals, the road map objectives for each goal, and the recommended areas for research and technology development. For many of the reduction goals, the committee identified several road map objectives. The last two columns in Table 10-1 list the areas of technology development and research with the most potential for meeting the road map objectives listed in the middle column.

The committee focused most of its efforts on ways to reduce the principal weight-and-volume logistics burdens of fuel and ammunition; however, it also considered maintenance, repair, and refitting (particularly reducing the personnel and infrastructure needed to provide support capabilities), and spare parts. As shown in Table 10-1, the associated reduction goals for fuel are reduced fuel demand, improved system energy management, increased fuel energy density by weight, and reduced weight of lethal systems. The reduction goals for the ammunition burden are fewer rounds of ammunition per target and reduced ammunition weight. Improved reliability of systems was identified as the key goal for reducing maintenance and spare parts burdens.

Logistics support for individual soldiers is a critical burden for any army, past, present, or future. The significance of this burden cannot be measured in terms of total weight or transport volume. The committee identified two goals for reduction of soldier

TABLE 10-1 Logistics Burdens, Burden Reduction Goals, Road Map Objectives, Technology Development Areas, and Research Areas

Logistics Burden	Burden Reduction Goal	Road Map Objective	Technology Development Area	Research Area
Fuel (weight and/or volume)	Reduce fuel and energy demand	Lightweight materials for air and ground vehicles	Distributed M&S[a] environment Materials selection databases and information resources	M&S for materials design Advanced armor and protection concepts
		Airframe weight; engine design	Distributed M&S environment	Novel air mobility concepts
		Minimally crewed vehicles	Distributed M&S environment Subsystem automation	Robotics
	Improve system energy management	Mobility systems evaluation	Distributed M&S environment (mobility systems) Fuel-economy specifications Driver training Hybrid vehicles evaluation	Active suspension
		Terrain awareness	Look-ahead sensors and systems Mobility models	Terrain sensor concepts
	Increase fuel energy density by weight	New energy delivery systems	Energy system modeling Compact nuclear power	Hydrogen storage
	Reduce lethal system weight	Lethal systems performance	Distributed M&S environment (lethal systems)	
Ammunition (weight and/or volume)	Reduce rounds per target	Situational awareness	Communications, sensor, and decision support systems; data integration and filtering Unmanned aerial vehicle and unmanned ground vehicle systems	C4ISR[b] supportability and robustness Artificial intelligence, robotics
		Precision guidance	Affordable small integrated guidance systems	Improved sensors, onboard processors, packaging, and controls

		Lethal systems performance	Distributed M&S environment (lethal systems)	
	Reduce weight per round	Energetics and warhead materials	Warhead materials M&S, evaluation Insensitive munitions	Advanced energetic formulations Insensitive energetics
		Lethal systems performance	Distributed M&S environment (lethal systems)	
Maintenance (refitting and repair)	Improve system reliability	Systems design for reliability	Distributed M&S environment with reliability metrics Materials selection databases and information resources	M&S of materials for application-specific reliability
Spare parts (weight and/or volume)	Improve system reliability	Systems design for reliability	Distributed M&S environment with reliability metrics Materials selection information resources	M&S of materials for application-specific reliability
Soldier systems and sustainment (weight)	Lighten soldier load	Compact power	Systems engineering of power demand	Microelectromechanical systems Nuclear batteries
		Lightweight protection systems (armor, chemical and biological agents, radiation)	Integrated protective garments and shielding	Novel materials
	Increase soldier effectiveness	Medical, nutrition, fitness	Life support systems	Nutrition; physical and mental augmentation concepts
All of the above	Optimize systems	AAN logistics trade-off analysis	Distributed M&S environment	
Inefficient logistics	"Just-right" logistics	Logistics situational awareness	Logistics command and control	C4ISR supportability and robustness

[a] Modeling and simulation
[b] Command, control, communications, computers, intelligence, surveillance, and reconnaissance

logistics: lightweight, compact systems for individual soldiers and increased soldier effectiveness.

The Army has begun a major effort to improve logistics delivery systems in response to *Joint Vision 2010* (see Chapter 2), and the Statement of Task for this study required that the committee focus on technologies that would reduce logistics support requirements of AAN combat systems (see Appendix A). Because of this, the committee did not assess technological opportunities to improve the logistics supply and distribution process itself. Nevertheless, technologies to improve logistics operations are very important. The reduction goal of "just-right" logistics is included in Table 10-1 to underscore the importance of SA technologies to logistics operations, as well as to combat operations.

Finally, a major theme of this report is the importance of system analysis of the kind associated with systems engineering. System analysis should begin early in the design process and continue through the stages of prototyping, testing, engineering development, and manufacturing. This capability is critical for weighing all of the requirements for reducing logistics burdens against one another, as well as for weighing the larger goal of logistics burden reduction against other AAN performance goals and requirements. Specialized forms of system analysis are also necessary for achieving many of the other road map objectives. Beginning in Chapter 3 and in various contexts throughout the other technical assessment chapters, M&S technology is discussed as supporting general and particular requirements for systems analyses and trade-off studies. Because M&S is relevant, and even essential, to so many of the road map objectives, it is treated first in the following summaries of the recommended research and technology areas.

For many important road map objectives, the key S&T needs identified by the committee are primarily technology developments or applied research for specific technology applications, rather than basic research. The committee identified a number of areas where basic research is essential to fill gaps in what is known (e.g., advances in hydrogen storage that might allow much higher energy per mass of storage system or innovative concepts for operational or tactical air mobility). However, some of these basic research areas are fairly narrow and limited (e.g., hydrogen storage). Others are better suited to strong Army participation in joint research (e.g., operational mobility) or to leveraging limited Army resources through partnering, rather than becoming a major focus of Army research.

Distributed M&S Technology

The committee found that distributed M&S technology, in various forms, can contribute to nearly all of the road map objectives listed in Table 10-1. This finding was not a presumption when the study began; it emerged gradually, in one functional area after another, from the information gathered and assessed by committee members. Although calls for increasing support for M&S have become commonplace in studies for the Army and other defense agencies, *this report focuses on improving and extending existing M&S tools to provide a useful and reliable environment for making system trade-offs that incorporate burden reductions with the performance goals of other primary systems.*

Trade-off analyses must be done at several stages prior to making the decision to field a system, especially in the early stages of requirements definition and design, as well as in the prototyping and other phases of design implementation. The committee recognizes that not enough is known about logistics support requirements, which are characteristics of entire systems, to predict them accurately from basic design elements (i.e., from first principles). Nevertheless, experience has shown that when logistical considerations are not addressed until the engineering and manufacturing development phases, design alternatives that could have significantly reduced logistics while maintaining adequate levels of other essential characteristics have already been eliminated from consideration.

Given the time frame and resource constraints of fielding AAN systems, M&S appears to be the best way for the Army to perform the requisite systems analyses. However, *the tools must be adequate to the task.* Only a few of the existing tools can provide realistic, quantitative modeling of the logistics associated with the operating conditions being modeled for a system or subsystem. Unless M&S tools have the capability to relate logistics impacts to other performance characteristics, they will be unusable for most of the purposes advocated in this report. For this reason, the committee believes that developing *adequate* analysis tools is a matter of the highest urgency and priority for achieving AAN capability by 2025.

The committee does not advocate that the Army develop one large M&S system, or even a tightly integrated "system of systems." In any given area, M&S tools must be able to pass data back and forth, creating a "distributed M&S environment." In some instances, closer coupling of several models, using one simulation or modeling "run" on coupled models, may be advantageous or even essential. But for most M&S applications discussed in this report, tight integration of modeling tools is not necessary, or even desirable.

Furthermore, M&S environments (sets of M&S tools) will vary, depending on the application area in which logistics burdens must be analyzed to optimize burden reduction and other performance goals. For example, Chapter 4 argues for an environment in which energy supply and distribution logistics can be effectively simulated, along with details of the AAN operational concepts that determine the "when, where, and how much" of energy demands. Chapter 4 also calls for an energy system management approach, incorporating M&S, for assessing technology options for reducing vehicle fuel demand. These two applications for M&S probably constitute two different "distributed M&S environments," with some capability for exchanging results and assumptions. The environment for modeling vehicle fuel demand is, however, the same as the distributed environment for vehicle design described in Chapter 5.

Another application area in which one or more M&S environment will be needed is in the analysis of alternative lethal systems discussed in Chapter 6. The M&S tools in this area must not only give realistic results about the logistics burdens associated with various options, but must also correlate the energy demand for these options with the overall energy supply and distribution M&S environment. Assumptions and results from lethal systems M&S can then be translated into operation-wide energy demands, and vice versa. Despite the necessity for data to be moved back and forth, the two environments are distinct with respect to the kinds of tools they must have to resolve logistics trade-offs. Assumptions and results of the lethal systems M&S environment(s) and the vehicle system M&S environment must also be transferable because the lethal systems will ultimately be subsystems of a vehicular platform.

Lightweight Materials for Air and Ground Vehicles

Technology Development Areas

The most important factor in reducing the demand for fuel on the battlefield is reducing the weight of battlefield vehicles. However, deciding how to reduce vehicle weight and still meet other performance requirements will require systems analysis using a distributed M&S environment for vehicle design (described in Chapters 3 and 5). *Substituting lighter weight materials for more conventional materials should be one of the objectives of vehicle design, as should increased reliability, defined in terms of AAN battle force mission requirements (see Chapter 7).* A frequent obstacle to the evaluation of lightweight substitute materials is the lack of information or the difficulty of accessing information about them. The Army should promote and support the development of information resources to help system designers obtain data on alternative materials.

The substitution of lightweight materials that also offer improved reliability or other performance advantages over more conventional choices is an area of broad applicability for reducing logistics burdens. Designing systems with lightweight, multifunctional materials and knowing how to manufacture them with high reliability and cost effectiveness are essential for developing combat systems with lower fuel burdens, as well as the other system performance characteristics required for AAN operations.

Research Areas

The committee selected two research areas related to substituting lightweight materials in vehicle systems. One is advanced armor and protection concepts; the other is the use of M&S tools to design microstructural versions of materials and the processing techniques to manufacture them efficiently.

The diversity of projectile threats and of possible combinations of technological approaches to protecting a ground or air vehicle will require designers of AAN vehicles to think in terms of a vehicle protection as a subsystem of the vehicle (see Chapter 4 and Appendix D). For instance, the protection system of an AAN vehicle might combine components of stealth and active protection with a lighter weight reactive armor. The Army should explore options for an optimal protection subsystem considering the mission requirements of the vehicle and taking into account the full range of projectile threats. *The weight of the protection subsystem components and the implications for fuel demand must be design criteria.* New armor building blocks and new architectures for armor should be investigated in the context of this broad perspective.

Some elements of biomimetics are relevant to this broad perspective, but other approaches to materials research, such as the development of lightweight alloys and functional-gradient intermetallics, ceramics for both organic-matrix and metal-matrix composites, and microstructured ceramics, should also be included. In the future, materials for components and substructures should be chosen to meet the full complement of performance objectives, such as structural and low-observable values, reduction in fuel demand through lighter system weight, and greater mission reliability, as well as the more traditional projectile defeat (armor) values.

The Army is currently considering a new SRO focused on advanced armor and protection concepts that reduce or eliminate dependence on heavy materials and vehicle structures. The SRO should include *materials research to increase the overall mission reliability of AAN systems as well as reducing weight.* A substitute material that can reduce the weight of a vehicle system must also meet all of the performance requirements of the particular application and must add less mass to the total system than conventional options. If known materials lack one or more of the required characteristics, computational approaches and modeling tools can be used by materials scientists to study, and even design, new materials with microstructures that can be controlled during processing. Electronic substrates, for example, depend on M&S tools for design and assessment of candidate microstructures and processing methods so that they can be efficiently produced in large quantities.

The current SRO in biomimetics addresses some aspects of this research. It includes research, for example, in which a biologically formed microstructured material is the starting point for replicating or adapting structural patterns that have been selected through natural evolution to provide high values in certain functional properties. Often the structural patterns of these biological materials are the reason these functional characteristics can be achieved with much less weight than conventional industrial materials with the same characteristics.

In computational approaches to materials design and in M&S of innovatively structured materials, as well as in biomimetics, the Army should continue to stimulate research, continue to be involved in the information and application-development networks with academic and industrial partners, and look for opportunities to leverage its resources by actively participating in joint-service and other programs to increase the knowledge base in this field. One opportunity for leverage might be in the commercial development and use of microstructural models to design manufacturing processes.

Airframe and Engine Designs

In Chapter 5, the committee discussed the problem of providing an AAN battle force with the operational mobility required by the AAN concepts. There are no airborne (or off-the-ground) candidates for providing tactical mobility for an entire AAN battle force that can maneuver in three dimensions at five times the speed of current ground combat vehicles, and use less fuel. To meet these requirements, *the Army will have to find novel, nonconventional air mobility concepts.* Even a demonstrated technology like the WIG (wing-in-ground) aircraft will require a great deal of both basic and applied research. Therefore, the committee listed airframe and engine design as a research area in Table 10-1.

Whether or not the Army finds promising novel options for operational and tactical air vehicles, reducing the fuel demand of air vehicles must be an objective. A distributed, hierarchical M&S environment can help in designing airframes and engines for increased fuel economy. Chapters 4 and 5 focused on the importance of this kind of M&S environment for ground vehicles, but an analogous argument can be made for air vehicle system design and logistics trade-off analyses. Foundations for some of the engineering-level components of this environment already exist—for example, the IHPTET program for the commercial development of high-performance turbine engines and the airframe design environments used by the aviation industry.

The Army should ensure that it has access to tools that can simulate the logistical performance, as well as other performance characteristics, of its airborne systems. Like the M&S environment for ground mobility, the "air mobility M&S environment" must provide links from the engagement levels described in Chapter 3 down to the subsystem and component levels of air vehicle design, with the capability of feeding design results from lower levels back up to the vehicle system and engagement levels. If a search for nonconventional air mobility does turn up promising candidates, the M&S environment will be essential for maturing the technology and fielding logistically competent systems by 2025.

Unmanned and Minimally Crewed Vehicles

Reducing crew size can reduce the fuel demand of battlefield vehicles primarily by decreasing the amount of vehicle structure (hence weight) required for substructures, such as the cockpit and the protection subsystem (armor). The potential for reducing the total system weight and the design trade-offs with other performance objectives will have to be analyzed and optimized using a distributed M&S environment.

Although UGVs are likely to have many uses in both AAN and Army XXI operations, subsystem automation appears to be a more reasonable, evolutionary approach to reducing the crew complement in general-purpose combat vehicles. If a combat unit of vehicles (a squad) is considered as a "fighting system," one or more of the vehicles could be an uncrewed subsystem controlled and supervised by a human unit commander in another vehicle. As Army and DARPA technology demonstrations of UGVs for specialized functions continue, the technology of subsystem automation can be converged with the technology of specialized uncrewed vehicles with a human controller/commander nearby.

For the sake of simplicity, the general field of research relevant to subsystem automation and autonomous mobility is listed in Table 10-1 as "robotics." Relevant aspects of research include control theory and control system engineering, which are considered a part of the field of artificial intelligence.

Mobility Systems

Designing and fielding AAN combat vehicles that incorporate highly efficient energy management while meeting other performance requirements will require thorough evaluations of the vehicle as a system from the concept design forward. Although some technologies, such as hybrid drive vehicles, have been widely accepted in the Army community as increasing vehicle fuel economy, *the committee believes that total system evaluations shall be done in the context of AAN mission requirements and operational concepts.* Evaluations should not be focused on maximizing any one performance goal, even fuel economy. With new technologies in intelligent engines, energy storage and recovery, active suspension, and terrain SA, system energy demands can be managed more efficiently. The capability of dynamic management must be designed into the vehicle system.

For ground vehicles, the capabilities of the driver will be a significant factor. Driver training for AAN operations will have to include the management of energy demand in the context of the cross-country mobility goals for the AAN battle force.

In Chapter 4, the committee endorsed a recommendation that has been made in previous Army-sponsored studies but has not yet been implemented. This is probably the simplest way to ensure that evaluations of mobility systems take fuel demand seriously and that optimum energy management systems are incorporated into AAN vehicles. *All vehicle procurements should include a clear, unequivocal, and easily measurable limit on vehicle fuel consumption.*

Terrain Awareness

Terrain awareness, like SA generally, is very important to meeting performance goals other than in logistics supportability. For example, a high level of terrain awareness will be essential to tactical planning and high cross-country speeds. Terrain awareness is listed in Table 10-1 to emphasize its importance for improving the energy management of ground vehicles. The key enabling technology areas for terrain awareness are look-ahead sensors and systems. Mobility models will also facilitate the design and assessment of terrain awareness technologies.

Look-ahead sensor systems will be one subsystem of the SA system for terrain awareness. Real-time data on current terrain conditions in the vicinity of the vehicle and the vehicle's projected course will be used to update the terrain database and SA sensor information stored in the vehicle (Chapter 6). Technology for terrain awareness is being developed at TARDEC, WES, and the U.S. Army Corps of Engineers Topographic Laboratory.

Potentially relevant research on new sensing methods and processing methodologies for assessing soil conditions, penetrating foliage and ground cover, and evaluating other terrain factors is being conducted by academic-industrial networks, which are motivated primarily by potential commercial applications but which offer the Army an opportunity to leverage its resources. The Army's SRO for intelligent systems is also a venue for tapping into broader research in sensing and imaging.

The mobility models will provide a virtual test bed for assessing the logistical consequences of specific aspects of terrain awareness coupled with maneuver doctrine and tactics to conserve fuel while meeting other performance goals. The mobility models will have to incorporate the terrain conditions that are recognizable to the candidate terrain awareness system and realistically simulate the consequences of the vehicle's interaction with the terrain on performance (e.g., ground speed, maneuverability, and avoiding or traversing obstacles) and fuel consumption.

New Energy Delivery Systems

A reliable fuel supply system is critical for a modern land combat force. The Army's exploration of significant changes in the fuel supply system to facilitate AAN operations and decrease logistics burdens should be based on an adequate model of the entire fuel supply system. The model should include a realistic simulation of the significant logistics considerations and their impacts on the fuel supply system and the war-fighting organization. The AAN war-gaming process has recently begun to incorporate modeling of fuel-supply logistics at the strategic, operational, and tactical levels. *An immediate objective should be the realistic coupling of a fuel-supply model to the fuel demands of AAN system concepts being tested in a war-game.* The techniques and systems used to achieve this modeling capability could also be used for fuel-system trade-off analyses, mission planning, and training exercises.

The modeling of energy system capabilities and energy requirements, based on trade-off analyses, including quantified logistical savings, may lead to totally new energy delivery paradigms for the AAN battle force. As a radical alternative to the current delivery system, which is based on transporting a petroleum-based fuel (diesel) for use in internal combustion engines, the committee investigated using hydrogen as a battlefield fuel for combustion engines and fuel cells. A hydrogen production facility at the staging area could be powered by a compact nuclear reactor.

Technological developments to support this radical alternative include scaling up the existing technology for compact nuclear reactors and improving the energy output per unit mass of electrolysis units that produce hydrogen from water. Although these developments seem feasible in the AAN time frame, a more difficult obstacle will be the development of lightweight, compact storage facilities for the hydrogen fuel. Unless all of these issues can be resolved in favor of this radical alternative, the existing system will be difficult to beat, although it can be improved by careful system optimization.

Lethal Systems Performance and Reduced System Weight

The principal focus of reducing logistics demands for lethal systems is reducing the ammunition burden. However, large lethal systems have substantial weight and require energy (fuel) to move them strategically and operationally, as well as tactically (on the battlefield). Some of the proposed alternatives to conventional chemically propelled projectile systems, such as the EM and ETC concepts, in effect trade part of the ammunition burden for increases in fuel. Both of these concepts require that fuel energy be converted to electrical power to propel the projectile, which means more fuel is required to move the heavier system, which must include an energy conversion and management subsystem.

Depending on the details of the technology and its operational profile, trading ammunition weight for an increase in fuel weight may increase or decrease the total logistics burden. The committee found no evidence that these trade-offs are being considered systematically. In fact, the committee was unable to find data on the quantities of fuel and ammunition used in past military operations that would be adequate to study past burden trade-offs. The presence in Table 10-1 of this objective is intended to remind the Army that the logistics trade-off analyses for any system should include *all* logistical considerations. Comparisons of alternative systems with respect to logistics burdens and performance characteristics including logistics should address all of the relevant burdens.

Situational Awareness and Precision Guidance

AAN operational concepts, as reflected in terms such as "precision maneuver" and "precision fires," assume a *near perfect* level of SA (see Chapter 6 and Appendix F). From a logistical standpoint, this essential SA is not a burden that can be measured in weight or volume. Rather, it is a critical necessity, a logistical choke-point; *any loss or degradation in the supply of SA information to AAN combat units can have cascading consequences, up to and including total defeat.* Although the committee was primarily concerned with logistics burdens reflected in weight and volume, this critical requirement for near-perfect SA was so ubiquitous across AAN technology applications that the committee felt compelled to note areas where AAN planners seem to be taking SA for granted.

In addition to the need for near-perfect SA in all aspects of AAN engagement concepts, SA technologies and their applications could significantly reduce the ammunition burden. With near-perfect SA, force dispositions and environmental conditions would be known precisely, which would improve the effectiveness of precision guided lethal systems and reduce the number of rounds required (and the number of rounds fired) per target. *SA and precision guidance have the most potential to reduce the ammunition logistics burden of all technology applications assessed by the committee.*

Technology Development Areas

There is considerable overlap in the technology development and research areas that would contribute to meeting the road map objectives of SA and precision guidance. Many of the basic electronic, electro-optical, and data processing technologies necessary for SA technology applications in Table 10-1 (communications and sensor systems, decision support aids, data integration and filtering) are also applicable to the affordable, small, integrated guidance systems required for precision guided missiles and munitions.

In the AAN time frame, UAVs and UGVs will be important sensor platforms for a wide range of C4ISR applications, ranging from intelligence preparation of the battle space and real-time communications at all levels of command, to tactical scouting and targeting for individual fighting units. The many active development programs for UAV and UGV sensor platforms throughout DoD and other government agencies, such as the NRO and NIMA, as well as the Army, should be reviewed periodically to determine whether they are collectively addressing AAN requirements. If necessary, the Army should identify and set priorities to redirect these programs.

Research Areas

All of the research areas on basic and applied knowledge relevant to the SA technology applications will contribute to the near-perfect SA for AAN missions. The committee chose to highlight research on C4ISR supportability and robustness because of the significant unresolved issues in these areas. Four current Army SROs (in nanoscience, smart structures, mobile wireless communications, and intelligent systems) support some (but not all) aspects of SA technology. Also, the intelligent systems SRO should enable the Army to focus on Army-specific basic research to support UGV technology. This research will continue to draw on advances first tested and used in UAVs or undersea vehicles (assuming that support continues for defense-relevant research in robotics, control theory, and engineering for unmanned vehicles and the C4ISR enabling technologies that apply to UGVs and UAVs). Other research areas to support advances in precision guidance, include the fusion of on-board sensors, reliable, inexpensive compact packaging, and sensor-actuator integration and control.

Reducing the Ammunition Burden through Lethal Systems Performance

Besides SA and precision guidance, other performance characteristics of weapon systems (e.g., range and reproducibility of propelling force) also contribute to reducing the number of rounds required per target. Significant trade-offs (with respect to reducing the weight of a round) among alternative designs for a given concept or competing concepts might be possible. Reductions in ammunition burden must be considered along with the fuel requirement for moving or energizing alternative weapon systems. Another logistics-related consideration is the size of the crew required for the weapon system, compared to alternative systems with similar functionality. The factors related to reducing logistics burdens should be assessed along with lethality performance characteristics in the context of clearly identified AAN lethality requirements.

The committee found no obvious winners among the potential alternatives for major weapon-systems, such as the main armament of AAN "front line" combat vehicles or the fire support systems that might be integral elements of a battle force. *This absence of clear winners reflects the lack of relevant data rather than equal potential performance of the enabling technologies or system concepts.* Even at the level of broad technology options, such as liquid propellants versus modular solid propellants, the available information on AAN requirements and logistics-relevant performance of the competing technologies is insufficient for the Army to make an informed choice.

The projectile weapon-system concepts and enabling technologies reviewed by the committee have already been in development for more than the time remaining until system choices must be made for the first generation of AAN platforms. So the lack of relevant data (even of estimates or reasonable guesses) cannot be explained by the novelty of the technologies or basic system concepts. The ongoing development programs have simply not provided the base of data for making systems-level comparisons and trade-off decisions that take logistics burdens into account. *To remedy this situation, the Army should leverage the existing R&D programs in projectile weapons and supporting technologies to provide data for modeling system alternatives and making rational trade-offs.*

Data on logistics support requirements should be compiled for each enabling technology or system concept. By assessing these disparate programs and development efforts from the standpoint of their contributions to a hierarchical simulation of system options and informed design trade-offs, the Army will be able to determine where modifications or additions should be made to the S&T base.

Energetics and Warhead Materials

Improving the performance of the energetics (propellants and explosives) in a missile or projectile round can reduce the mass and volume per round without compromising lethality or can reduce the number of rounds required to achieve the desired effect. Improving uniformity of burn, for example, can improve precision thereby reducing the average number of rounds required to hit a target. Energetics with higher energy density may enable the delivery system to be lighter and smaller.

Less obvious, but equally important in terms of burden reduction for a given technology investment, are the indirect effects of less sensitive munitions. The best chances for burden reduction are from technological advances that would improve the performance of an energetic as a propellant or explosive while decreasing its sensitivity to heat or shock.

The Army should continue (or increase) its participation in the IHPRPT program while focusing on meeting the needs for AAN systems, including missile systems that can be launched from small vehicles, reach high velocity quickly (Mach 6 and greater), produce minimal smoke, and are insensitive to thermal and shock threats. These systems must also be throttleable and adaptable to various missions. Solid-fuel ramjets are an option to explore for high-speed, relatively low-cost missiles for AAN operations.

The development of energetics that are insensitive to shock and thermal threats must be based on a basic understanding of the mechanisms of insensitivity. This understanding can be achieved through studies in quantum chemistry, chemical and thermal decomposition, and improved computer modeling of shock and thermal events. The Army should keep abreast of ongoing research at the national laboratories on new, high-energy energetic materials (such as metastable interstitial composites) that may offer tailorable output and improve energy-density over current energetic fills.

The Army should develop insensitive, high-energy warhead fills and novel mitigation-barrier materials to eliminate fratricide. The Army should also support the development of reactive, three-dimensional detonation physics hydrocodes for warhead design and target interactions.

Systems Design for Reliability

The reliability requirements for AAN systems should be defined first at the functional level of meeting mission requirements. The war-fighters and technologists engaged in the AAN process should work together to define objective, quantifiable, accountable terms for mission reliability, beginning at the highest levels of engagement analysis and proceeding down to reliability requirements for individual systems (platforms or vehicles). The S&T community should ensure that the lower levels of system analysis include reliability-related performance metrics during design and system trade-off studies.

The committee identified two technology development areas as critical for designing systems for reliability. First, the distributed M&S environments used to support system design and logistics trade-off analysis should be extended to provide the following five elements, which are not included in current M&S tools used by the Army:

- models that represent the system properties and environmental conditions that affect AAN mission reliability requirements
- measurable reliability-related requirements for models at every level in the M&S hierarchy
- iterative simulations up and down the hierarchy of models in the design and engineering process
- provisions for obtaining valid data on lesser-known design options that could contribute to meeting combinations of AAN performance goals (including mission reliability)
- maintenance of mission reliability, defined by assessable reliability requirements, as a performance objective for design and engineering development

As the committee noted in the discussion of the road map objective of lightweight materials for air and ground vehicles, necessary improvements in information resources for materials selection at the component level of the hierarchy include improved data and representations for assessing the reliability-related features of materials. The discussion of lightweight materials also covered a research area that is important for the long-term innovation of materials that are more reliable for specific applications, as well as lighter in weight and able to meet other performance requirements. If reliability requirements are conveyed down the structural hierarchy from the systems level to the level of requirements for materials for components and structures, materials research could contribute decisions about a range of candidates already available to designers. The areas of materials research relevant to improving reliability are (1) the mechanisms of failure and the incorporation of this knowledge into M&S tools, (2) the selection or design of materials that can meet AAN requirements, including reliability requirements, that familiar materials cannot meet, and (3) embedded prognostic sensing technology in designing structures and components. The Army should continue to leverage its resources in these areas of research through networking with industry and academic partners and through active participation in joint-services programs.

Compact Power

Personal power sources for the dismounted soldier is a major logistics concern, not because of the tonnage involved but because the effectiveness of individual soldiers is a combat necessity. For meeting this objective, the committee supports the recommendations on research areas and relevant technologies of an in-depth NRC study of energy-efficient technologies for the dismounted soldier (NRC, 1997a).

Long-term research to increase dramatically the amount of energy stored per unit weight carried by soldiers will require a different approach than traditional electrochemical batteries. The compact power SRO has focused research on fuel cells and on microturbines, a high-risk, high-payoff alternative to batteries. Prototypes of rechargeable fuel cell systems with high potential for soldier application have already been demonstrated. A fundamental departure from electrochemical batteries would be nuclear batteries providing for direct conversion of low-level nuclear energy to electrical power, which may be feasible with icosahedral borides or another semiconductor with photovoltaic properties.

Lightweight Protection Systems for Individual Soldiers

The ideal protective garment for the soldier of the future will have to be multifunctional. In addition to preventing or minimizing injury from small-caliber rounds and shrapnel, it should also protect the wearer from biological and chemical threats and from residual radiation following a nuclear blast. Protection from the NBC (nuclear, biological, and chemical) threats requires a barrier to air exchange with the external environment, which implies that thermal management and purification of respirable air will also be necessary. At the same time, this garment or protective system must not impede the soldier's ability to see and hear or to move and react quickly to the physical demands of a combat environment. Indeed, the advantages of personal sensor systems and exoskeleton arrays is to enhance the perceptions and physical strength of soldiers.

For each of these functional requirements in isolation, there are technologies that at least offer promise, if not near-term practical implementation. From the perspective of decreasing logistics demand, the more difficult challenge is to meet all of the functional requirements and objectives in one set of protective gear. A suitable level of functionality in each area must be integrated into an optimally performing, highly reliable, protective and supportive system of combat gear. Since weight is a primary consideration for soldier logistics, the system may have to be modular so different combinations of functionality could be supplied and distributed for use on the AAN battlefield.

The Army has been successful in meeting Army XXI soldier requirements by approaching the "soldier as a system." Technology development programs to address these needs, including programs in chemical and biological defense and the Twenty-First Century Land Warrior Program, are developing technologies that can be inserted into functional open-system architectures. A similar strategy that incorporates AAN logistics trade-off analyses is recommended to minimize logistics support requirements for AAN soldier systems.

Advances in Combat Medicine, Nutrition, and Soldier Fitness

The logistics of sustaining an individual soldier *physiologically* for the duration of an AAN combat pulse or mission are more complicated than identifying technological possibilities for meeting one or another requirement or advancing toward one or another desirable capability. The human soldier is the Army's most complicated system. Attempts to alter radically the proven methods of sustaining soldiers under combat conditions will require a careful assessment of the effects on overall performance. The consequences may be indirect, delayed, or cumulative and may have little or no immediate or easily observable effects.

The Army is pursuing many avenues in this area; most of those briefed to committee members should be ready for extensive testing well before the AAN time frame. The area clearly has high potential for increasing the combat effectiveness of AAN soldiers. However, the committee did not have the expertise to make an in-depth assessment of technological opportunities in this area.

AAN Logistics Trade-off Analyses across Burden Reduction Goals

This report has repeatedly emphasized that burden reduction goals should not be pursued in isolation from other performance objectives, and vice versa. It is equally true that any burden reduction goal cannot be pursued in isolation from other logistics burdens that affect the performance profile of a system. The small unit and force-on-force engagement levels of the distributed M&S environment described in Chapter 3 can be particularly valuable for the design analyses for assessing consequences in terms of logistics burdens (as well as other performance objectives) and for making necessary trade-offs. However, the results will only be as realistic and dependable as the relationships built into each level of the M&S hierarchy.

Situational Awareness for Logistics Operations

Technology to improve logistics operations was not part of this study. However, the committee was briefed on the Army's ongoing plans for a revolution in military logistics to achieve the concept of *focused logistics* for *Joint Vision 2010.*

The basic technologies that underlie these planned advances in logistics operations overlap considerably with the technologies that will enable the SA required to support precision guidance terrain awareness, and many other AAN performance objectives that this report does address. Furthermore, many of the same issues related to the supportability and robustness of military C4ISR systems have significant implications for logistics operations.

11

Conclusions and Recommendations

This chapter presents the general conclusions and recommendations that follow from the study.

Conclusion 1. The Army can reduce logistics demand for Army After Next combat systems.

Fuel and ammunition will continue to be the dominant logistics burdens of an AAN battle force. Investments in research and technology development can achieve specific burden reduction goals. Reducing or eliminating the demand for fuel, ammunition, and spare parts will have a ripple effect by reducing the need for separate logistics units and personnel to support the battle force.

The primary ways to reduce logistics demand for fuel and ammunition include research and technology developments in modeling and simulation, lightweight vehicles and systems, and improved precision guidance systems. The demand for spare parts and maintenance support can be reduced by including reliability as a performance requirement at all levels of system design.

Recommendation 1. The Army should invest in the research and technology development areas listed in the last two columns of Table 10-1 to reduce logistics demand for Army After Next systems.

Conclusion 2. Technologies for improving situational awareness (SA) are critical to reducing logistics demands for AAN systems. SA is essential for fuel-efficient, high-speed mobility and for engaging targets efficiently and effectively, thereby reducing battlefield requirements for both fuel and ammunition. AAN systems will be even more dependent on SA technologies than those developed for Army XXI.

Recommendation 2. The Army should assume that currently contemplated standards of command, control, communications, computing, intelligence, surveillance, and reconnaissance (C4ISR) will not be adequate to support the near-perfect situational awareness requirements of an Army After Next battle force. The Army should ensure adequate funding for research and development of secure, robust, and supportable C4ISR systems and should adapt new information technologies to meet Army After Next requirements as they are identified.

Conclusion 3. The development of joint-service capabilities will affect the Army's ability to reduce AAN logistics burdens. Because future operational concepts for the Army and the other services will be derived from the DoD *Joint Vision 2010,* the AAN should be planned to take full advantage of research and technology developments sponsored by DoD and the other services.

Promising commercial programs are under way in both heavy-lift aircraft and high-speed ships that might provide the AAN with unprecedented strategic mobility from the continental United States to forward staging areas and, by 2025, perhaps even into the battle area. If the Air Force and Navy adopt new aircraft and ships, strategic lift capabilities provided to the AAN battle force and follow-on forces would be significantly improved.

Prospective enhancements in C4ISR and weapons systems developed by the other services can be integrated into AAN planning, thereby reducing the need for deploying parallel capabilities. Technologies developed to support SA and force projection for the other services might also be used for AAN systems.

Recommendation 3a. The Army should work to influence commercial developments in strategic mobility to ensure that new capabilities include military add-ons to the commercial designs. The Army should participate in design reviews with commercial developers to ensure that battle force requirements are met. (A similar approach was recommended in *STAR 21: Strategic Technologies for the Army of the Twenty-First Century.)*

Recommendation 3b. The Army should integrate the situational awareness and fire support capabilities of the other services into the Army After Next concept.

Conclusion 4. Revolutionary changes in battlefield mobility for an AAN battle force are unlikely to be attained before 2025. The committee found no combination of technologies that would be capable of simultaneously meeting hypothesized requirements for speed, weight, fuel consumption, survivability, and lethality for AAN fighting vehicles.

Current concepts for meeting AAN operational and tactical mobility goals do not provide for the desired increases in mobility or reductions in fuel consumption. The committee estimates that a future 15-ton wheeled combat vehicle able to attain cross-country speeds of up to 130 km/h over moderate terrain is technically feasible. Air carriers capable of meeting operational lift requirements for a force of 15-ton vehicles are also technically feasible, but these carriers may not be affordable and would add significantly to the overall fuel burden.

Recommendation 4a. If the Army After Next battle force requires a capability for cross-country mobility at speeds of more than 130 km/h, the Army will have to develop novel mobility alternatives. Research in novel technology areas, such as surface ground effects, will only be undertaken at the Army's insistence and should begin immediately.

Recommendation 4b. If 130-km/h cross-country mobility is adequate for Army After Next operations, the Army should develop requirements for a family of minimally crewed wheeled vehicles to perform battlefield functions.

Recommendation 4c. The Army should define its long-term requirements for operational and tactical mobility and work with the U.S. Department of Defense to clarify joint-service responsibilities. Research and technology development should be pursued on a department-wide basis to fulfill overlapping objectives of the Army and other services for the AAN time frame.

Conclusion 5. Reliability considerations (including reliability, availability, maintainability, and durability) have been routinely sacrificed for other performance characteristics. To reduce logistics demand for AAN systems, reliability must be treated on an equal basis with lethality, survivability, and mobility in the design process.

Recommendation 5. The Army should revise its design and source selection criteria for battle force systems so that reliability is considered on an equal basis with other mission-specific goals.

Conclusion 6. Logistics support for soldiers requires special attention because the individual soldier will be the most essential combat system in the Army After Next.

Advances that extend human physical capacity and reduce the need for medical support could lead to quantum improvements in soldier combat performance. Reducing the soldier's logistics support requirements would have a multiplier effect by increasing combat effectiveness and reducing logistics demand for medical support, water, food, and life support.

Recommendation 6. The Army should focus on the "soldier as a system" by ensuring adequate funding for research and technology developments to reduce the weight and bulk of the soldier's combat load and to extend the soldier's physiological and psychological capacities.

Conclusion 7. Technology solutions to reduce the logistics demands of Army After Next systems will not be simple.

The committee does not foresee breakthroughs in technology that will alter fundamental logistical considerations by 2025 for an AAN battle force. Therefore, the Army should apply technology directly toward achieving specific burden reduction goals rather than anticipating that a magic substitute for fuel or ammunition will be found.

The AAN shift away from heavy direct-engagement systems toward smaller, more versatile platforms capable of operating in diverse environments, including urban centers, will reduce the Army's traditional dependence on a "supply line" to meet fuel and ammunition requirements and will reduce the numbers of both combat and logistics personnel *in the battle area.* The dramatic improvements in mobility, survivability, lethality, and reliability necessary to ensure the success of a battle force will require that the Army focus now on ways of reducing the logistics support requirements of future combat systems.

Analyzing logistics trade-offs during the planning and implementation of systems will be critical. Of all advanced technologies considered in *STAR 21: Strategic Technologies for the Army of the Twenty-First Century,* computer simulation and visualization technology was recognized as the most relevant to the development of new Army systems. With improved modeling and simulation tools, the Army can identify, analyze, and evaluate alternatives and determine optimum system characteristics for reducing logistics demands at minimum expense. State-of-the-art modeling and simulation tools could also be used to test operational tactics and procedures, train soldiers, and verify doctrinal precepts.

Recommendation 7a. The Army should develop the necessary modeling and simulation tools for conducting logistics trade-off analyses at all levels of design, from small-scale components to fully integrated systems.

Recommendation 7b. To facilitate model development, logistical data from past military operations must be compiled and maintained in useful formats.

Recommendation 7c. Logistics trade-off analyses should be included in the Army's system acquisition and integrated logistics support processes.

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Appendices

Appendix A

Statement of Task

The study will address long-term Army science and technology investments likely to have the most impact on logistics requirements for the AAN. Conclusions, recommendations and rationale will be documented in a final study report provided to the Army. Over the course of the study, the following tasks are to be accomplished:

(1) Interact with the Army to thoroughly understand the importance of logistical considerations to successful battlefield operations and the likely impact of different enabling technologies on the need for logistics support.

(2) Review advanced concepts for soldier and battlefield systems contemplated for the AAN timeframe. Include consideration of the following: Future Combat System (FCS), Future Scout and Cavalry System (FSCS), Soldier as a System, Army Tactical Missile System (ATACMS), and their enabling technologies.

(3) Analyze the enabling technologies (e.g., 'smart' materials, microelectromechanical systems, etc.) on which systems contemplated for the AAN will depend in light of their likely impact on the need for logistics support. Classify the technologies according to the degree to which they are likely to require more or less logistics support. Propose alternative technologies that would diminish the need for logistics support.

(4) Identify and evaluate areas of research that, if supported by a long-term sustained Army investment, would enable systems and operational concepts to have reduced need for logistics support in the 2025 timeframe of the AAN. Affordability must be a major consideration. Also important is the ability to leverage investment of other services, other government agencies, and the private sector to influence the development of the technology.

(5) Develop recommendations for an Army R&D investment strategy that includes a conceptual framework, specific research objectives, and a roadmap to achieve the objectives.

Appendix B

Meetings and Activities

This appendix lists the presentations provided at the committee and panel meetings and other fact-finding activities by committee members during the course of this study.

Committee Meetings

First Committee Meeting, August 19-20, 1997 National Academy of Sciences, Washington, D.C.

Major General Robert H. Scales, Jr.
Army War College
The Army After Next Project, Knowledge and Speed
Major General John S. Cowings
Industrial College of the Armed Forces
Doctrine for Logistics Support of Joint Operations Joint Vision 2010
Dr. A. Fenner Milton
Office of the Assistant Secretary of the Army
(Research, Development and Acquisition)
Science & Technology Strategy for the Army After Next
Brigadier General Joe Arbuckle
Army Materiel Command
The Army 's Materiel Command
Lt. Colonel George Topic
Office of the Deputy Chief of Staff for Logistics, Department of the Army
Achieving a Revolution in Military Logistics . . . The Master Logistics Vision
Mr. Robert Dienes
Combined Arms Support Command (CASCOM)
Introduction to CASCOM

Dr. John A. Parmentola
Office of the Deputy Assistant Secretary for Research and Technology
Strategic Research Objectives and the Army After Next
Dr. Lewis E. (Ed) Link
U.S. Army Corps of Engineers
Logistics Support Requirements for Future Army Combat
Dr. Wolf Elber
Army Research Laboratory
Plenary Lecture Vehicle Technology Center
Colonel James Bald
Army Materiel Command
Force XXI and Emerging Technologies

Second Committee Meeting, October 1-2, 1997 National Academy of Sciences, Washington, D.C.

Dr. Ronald A. DeMarco
Office of Naval Research
Department of the Navy Logistics-Related 6.1 Research
Dr. Julian M. Tishkoff
Air Force Office of Scientific Research
Logistical Support Requirements for Future Army Combat Systems: Air Force Research Activities
Dr. Michael A. Stroscio
Army Research Office
Science for AAN Logistics Efficiencies: U.S. Army Research Office Programs for the Board on Army Science and Technology
Colonel Mike Starry
Army Training and Doctrine Command
The Army After Next Project: Knowledge and Speed
Mr. Charles T. (Terry) Chase
Pacific Northwest National Laboratory
Potential Logistics Applications for Strategic Research Objectives
Dr. John Gully
Defense Advanced Research Projects Agency
DARPA Research Activities

Lt. Colonel Henry Franke
Army Training and Doctrine Command
Army After Next Update to BAST's AAN Log Committee

Third Committee Meeting, December 15-16, 1997 National Academy of Sciences, Washington, D.C.

Mr. Rick Camden
Army Research Laboratory
Joint Logistics Advanced Concept Technology Demonstrations Project Office
Mr. Bill Crowder
Logistics Management Institute
AAN Logistics and Nuggets
Mr. Robert Dienes
Combined Arms Support Command
Army After Next Logistics Support Concept:
The AAN Logistics Franchise
Dr. Wolf Elber
Army Research Laboratory
AAN Logistics: The Invisible Cost Driver and Proposed SRO for Durability/Reliability Technology
Dr. Ali Haghighat
Pennsylvania State University
Methodologies for Particle Transport Simulation and Their Application to Reactor Dosimetry and Shielding (via teleconference)
Lt. General Paul Kern
Office of the Assistant Secretary of the Army
(Research, Development and Acquisition)
Army Acquisition Corps
SARDA Army After Next Activities
Mr. Bill Howell and Colonel Fred Tyner
Army Medical Research and Materiel Command
Sustainment Panel Briefing: Reducing the Logistics Tail
Dr. Robin Keesee
Army Research Laboratory
MANPRINT for AAN Logistics

Mr. Robert A. Rossi
Army Defense Ammunition Logistics Activity
Armaments Research, Development, and Engineering Center
Munitions Resupply Technologies for the Army After Next
Mr. Charles M. Shoemaker
Army Research Laboratory
Robotic Vehicle Technology Development for Future Ground Combat Systems

Fourth Committee Meeting, February 19-20, 1998 National Academy of Sciences, Washington, D.C.

Mr. Robert Dienes
Combined Arms Support Command
AAN Update
Mr. William Crowder
Logistics Management Institute
Emerging Technologies
Dr. Michael Dyson
Defense Advanced Research Projects Agency
Advanced Logistics Project, Joint Logistics Advanced Concept Technology Demonstration

Fifth Committee Meeting, April 29-30, 1998 National Academy of Sciences, Washington, D.C.

No presentations

Panel Meetings

Mobility Panel Meeting, October 22-23, 1997 Army Tank-Automotive Research, Development and Engineering Center Detroit, Michigan

Dr. Richard McClelland
Army Tank-Automotive and Armaments Command
U.S. Army Tank Automotive Research, Development, and Engineering Center
Mr. Roger K. Halle
Army Tank Automotive Research, Development, and Engineering Center
Army After Next (AAN) Concepts

Dr. Robert Bill
Army Research Laboratory
Fuel Efficient Army After Next
Mr. Charles Raffa
Army Tank Automotive Research, Development, and Engineering Center
Fuel Consumption, Weight, Speed, Alternatives
Mr. Bruce Brendle
Army Tank Automotive Research, Development, and Engineering Center
Crewstation Technology
Mr. Charles M. Shoemaker
Army Research Laboratory
DEMO III Concerted Technology Thrust
Dr. James Thompson
Army Tank-Automotive and Armaments Command
Advanced Armor Protection
Mr. Steven Caito
Army Tank Automotive Research, Development, and Engineering Center
Hit Avoidance Advanced Technology Demonstrator
Mr. Michael Reid
Army Tank-Automotive Research, Development, and Engineering Center
Electric Vehicle Program Briefing
Dr. Robert Bill
Army Research Laboratory
Advanced Aviation Concepts for Army After Next
Mr. Jeff Carie
Army Tank Automotive Research, Development, and Engineering Center
Composite Armored Vehicle Advanced Technology Demonstrator
Mr. Tony Comito
Army Tank Automotive Research, Development, and Engineering Center
National Automotive Center Programs
Mr. Robert J. Watts
Army Tank Automotive Research, Development, and Engineering Center
Technology Opportunities Analysis System (TOAS) Information Synthesis

Sustainment Panel Meeting, October 27-28, 1997 U.S. Army Research Office, Research Triangle Park, North Carolina

Dr. Michael A. Stroscio
Army Research Office
Science for AAN Logistics Efficiencies: Selected U.S. Army Research Office Programs
Dr. Wilbur C. Simmons
Army Research Office
Biomimetics
Dr. Linda Bushnell
Army Research Office
SRO on Intelligent Systems
Dr. Gary L. Anderson
Army Research Office
Smart Structures Research
Dr. John A. Bailey
Army Research Office
The Next Generation of Damage Tolerant Lightweight Armor Materials for the Protection of All Army Materiel and Personnel
Dr. David M. Mann
Army Research Office
Combat Vehicles for Reduced Logistics Burden
Dr. William A. Sander
Army Research Office
Strategic Research Objective (SRO) Mobile Wireless Communications
Dr. Richard J. Paur
Army Research Office
Compact Power Sources
Miss Colleen Cathcart
Natick Research, Development and Engineering Center
AAN Logistics Efficiency Study
Mr. Michael W. Deckert
Army Materiel Systems Analysis Activity
Sustainment Cost Savings through Physics-of-Failure (PoF) Reliability Modeling

Lt. Colonel Tom Light
USA Aviation Applied Technology Directorate
Army Aviation Operation and Sustainment
Ms. Lois H. Aymett
Missile Research, Development and Engineering Center
Logistics Initiatives for AAN

Mobility Panel Meeting, November 13-14, 1997 U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi

Dr. Andrew W. Kerr
Ames Research Center, Army Research Laboratory
V/STOL [vertical or short take-off and landing] Aircraft Summary
Dr. William F. Marcuson
Waterways Experiment Station
Defense S&T Reliance
Dr. Bill Willoughby
Waterways Experiment Station
Sustainment Engineering, WES Mobility Engineering and Research Implications
Miss Denise Bullock
Waterways Experiment Station
Mobility Factor Inference and Sensitivity Analysis
Ms. Patricia M. Sullivan
Waterways Experiment Station
Soil Moisture Strength Prediction to Support Worldwide Military Operations
Dr. Niki C. Deliman
Waterways Experiment Station
Stochastic Mobility Modeling, Robust Mobility Modeling and Stochastic Applications
Mr. David A. Horner
Waterways Experiment Station
Advanced Mobility Modeling
Dr. David W. Pittman
Waterways Experiment Station
Airfields and Pavements to Support Force Projection

Dr. James Houston
Waterways Experiment Station
Logistics-over-the-Shore Technology

Mobility Panel Meeting, November 20-21, 1997 National Academy of Sciences, Washington, D.C.

Dr. Terry Aslarge, Sandia National Laboratories and
Dr. David Emin, University of New Mexico
Novel Energy-Conversion Devices of cosahedral Borides
Dr. Robert Nowak
Defense Advanced Research Projects Agency
DARPA Advanced Energy Technologies Program
Dr. Richard J. Paur
Army Research Office
Compact Power Sources and Hydrogen Technologies
Dr. Ira F. Kuhn, Jr.
Directed Technologies, Inc.
Affordable Hydrogen Supply Pathways for Fuel-Cell Vehicles
Mr. Lawrence D. Johnson
Army Research Laboratory
Future Combat System
Mr. Mark Delmonico and Mr. Scott Story
U.S. Marine Corps Amphibious Armored Assault Vehicle (AAAV)
Advanced Amphibious Assault Vehicle Science and Technology Overview
Mr. Bob Carrese
Bell-Boeing Tiltrotor Team
V-22 "Osprey" Program Update
Dr. George C. Joy
U.S. Department of Commerce
Partnership for a New Generation of Vehicles
Dr. Marilyn Freeman
Army Research Laboratory
The Army After Next Project and Mobility Integrated Idea Team
Dr. Dave Shaffer
Army Materiel Systems Analysis Activity
An Overview of Army Weapons Systems Analysis

Engagement Panel Meeting, November 24-25, 1997 Army Research Laboratory, Aberdeen, Maryland

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Mr. Charles M. Shoemaker
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Robotic Vehicle Technology Development for Future Ground Combat Systems
Dr. John A. Bailey
Army Research Office
The Next Generation of Damage Tolerant Lightweight Armor Materials for the Protection of All Army Materiel and Personnel
Mr. Albert E. Warnasch
Army Armaments Research, Development, and Engineering Center
Army After Next
Ms. Gloria P. Wren
Army Research Laboratory
Liquid Propellant Gun Propulsion Technology
Dr. William Oberle
Army Research Laboratory
Electrothermal-Chemical Gun Propulsion Technology
Dr. William D'Amico
Army Research Laboratory
Canon Artillery More Accurate Projectiles and Fewer Fuzes
Dr. William de Rosset
Army Research Laboratory
Armor/Anti-Armor Brief
Dr. John W. Gowens
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Communication and Network Systems Division
Dr. Jagdish Chandra
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Computer and Software for AAN
Dr. Jeff Cerny
Army Aviation and Missile Command
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Sustainment Panel Meeting, December 5, 1997 U.S. Army Natick Research, Development and Engineering Center, Natick Massachusetts

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U.S. Army Soldier Systems Command and the Army After Next
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Ballistic Protection for Individual Survivability
Mr. Matthew Whipple
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Lightweight Chemical Protection for Individual Survivability
Mr. Thomas H. Bagwell
Army Tank-Automotive Research, Development and Engineering Center
Water Supply Initiatives for Army After Next

Lt. Colonel John P. Obusek
Army Research Institute of Environmental Medicine
U.S. Army Medical Research and Materiel Command: Support to Army After Next Logistics Efficiency
Mr. Brian Croner
Natick Research, Development and Engineering Center
Three-Dimensional Anthropometric Data Acquisition and Analysis For Clothing and Equipment System Design
Mr. Edward J. Doucette
Natick Research, Development and Engineering Center
Airborne and Ground Mobility Science and Technology

Site Visits

Army Vehicle Technology Center, Cleveland, Ohio, November 21, 1997
Lockheed-Martin Corporation, Atlanta, Georgia, December 10, 1997
Sandia National Laboratories, Sandia, New Mexico, January 14-15, 1998
Army Logistics Integration Agency, Alexandria, Virginia, March 26, 1998
University of Texas Center for Electromechanics, Austin, Texas, April 10, 1998
Army Research Lab Institute for Advanced Technology, Austin, Texas, April 10, 1998
Army Ames Research Center, Moffat Field, California, April 12, 1998
Patuxent River Naval Air Station, Lexington, Maryland, June 11, 1998

Appendix C

Technologies for Materials Selection and Design

Chapter 3 described how modeling and simulation (M&S) technology can enable the development and integration of a hierarchy of simulation tools into an interactive system design environment, or "virtual proving ground." Without this modeling environment, the trade-off analyses required to meet Army After Next (AAN) logistical goals and other performance requirements cannot be accomplished within the time and resource constraints the Army faces. Figures 3-1 and 3-2 showed that the selection of materials is one of the many engineering considerations required for detailed designs of components and subsystems using this simulation environment.

This appendix focuses on the technology and information requirements for extending the "virtual proving ground" approach down to the level of *materials selection,* and even to the lower level of the *design of new* (or newly structured) *materials.*[1] The hierarchical relations in Figure 3-1 will always hold: the performance requirements that determine the properties of a candidate material flow down from the higher levels of function and structure in the hierarchy. The duty cycle(s) and structural demands of the components and subsystems in which a material is to be used determine which properties are critical for that application.

When this structure-function hierarchy is traversed upward, it shows how the performance of a material for a specific use in a component (or subsystem) depends on the material's properties and their interactions with the properties of other materials. To select a material and model its performance for a particular application, the key properties must either be known from previous experience with the material or inferred from other knowledge about the material. Figure C-1, which shows the considerations that feed into the component design level of the hierarchy, shows that there are two opportunities (the two lower-right ellipses) at which a design engineer can select candidate materials to feed into the modeling of the component and subsystem design and analysis.

The first and most expedient opportunity is for the design engineer to have *information resources* about the physical properties of candidate materials, such as

[1] The National Materials Advisory Board of the National Research Council published two studies that cover important aspects of these two levels of materials engineering and design. The first report, *Computer-Aided Materials Selection During Structural Design* (NRC, 1995b), is particularly relevant to the first level of materials selection technologies and the information bases needed to support more extensive application of them. The second report, *Hierarchical Structures in Biology as a Guide for New Materials Technology* (NRC, 1994b) investigates the principles and potential approaches for biomimetic approaches to designing innovative materials.

materials databases or selection charts. By applying materials selection principles derived from the requirements of an application, the designer can choose the best candidate materials—and the best material processing and fabrication techniques—and incorporate it directly into the component design being simulated in the virtual testing environment.

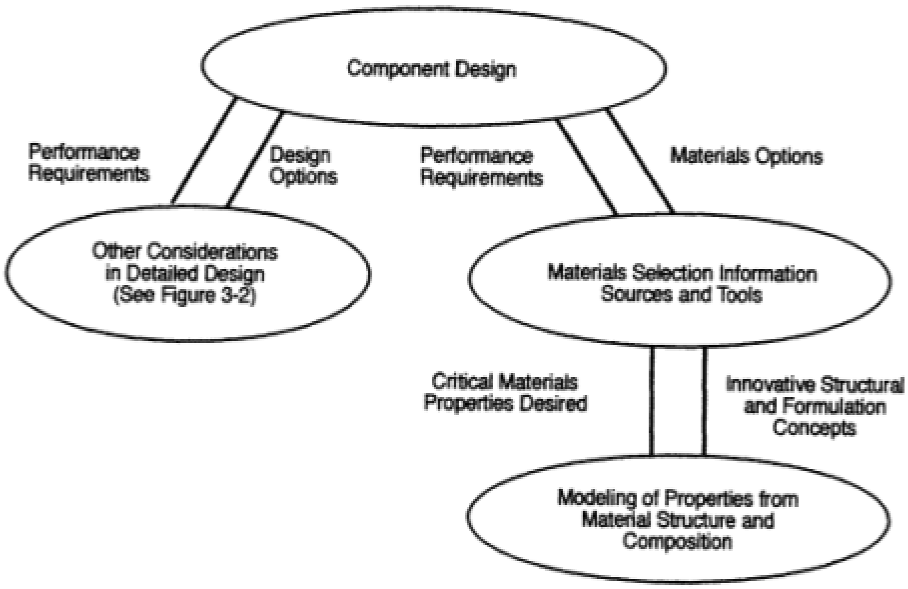

Figure C-1
Materials engineering technologies to support system design.

The second opportunity, depicted at the lowest level in Figure C-1, is used when well characterized existing materials cannot provide the combination of properties required for the application (or more realistically, do not come close enough to the figures of merit for all application-critical requirements). This strategy incorporates knowledge from materials science into modeling environments for designing and controlling the production of innovative materials with specified properties. These new concepts for structuring or formulating materials could yield new alloys, intermetallics, composites with ordered microstructures, and materials with hierarchical structures.

Although both of these levels are, to a limited extent, feasible with existing technology, much can be done to improve the enabling *materials selection* and *materials design* technologies for solving issues raised by AAN requirements. These technologies have broad applications not only for advanced systems for defense but also for advanced systems for innovative commercial products. Therefore, the Army could leverage its resources by participating in research or application-oriented networks, sometimes as a supporter of basic research, sometimes as an information-sharer, and sometimes as a co-investor in production capacity or a product purchaser. An example of one way that government agencies, including the defense services and agencies, can participate in these leveraging opportunities is the 1995 workshop on strategic materials sponsored by the National Materials Advisory Board (NRC, 1995b).

Information Resources to Support Materials Selection

Designing a component or subsystem involves translating an idea or a market need into detailed specifications for a product. Each stage requires making decisions about the materials to be used. Often the design dictates the choice of materials, but sometimes a new product, or the evolution of an existing product depends on the availability of a new material. A vast number of materials are available to design engineers—sometimes 40,000 to 80,000 variations. Standardization reduces the number somewhat, but the continuing appearance of new materials with novel, exploitable properties increases the choices.

Materials selection during the design process is very important. For demanding systems, such as a new Army combat vehicle or rotorcraft, the designer will probably begin with materials selection handbooks that contain guaranteed minimum properties for materials that have been used extensively. For example, the Military Handbook V covers materials for which there are extensive information bases about properties and performance. If materials from this handbook are selected, a designer can depend on meeting minimum requirements at various levels of statistical confidence. If a material is not in this handbook, the designer cannot use it for safety-critical systems, such as aircraft. Even if the material could be used, the designer may not have reliable data on the critical properties for the design application. Unfortunately, the designer may be unaware of promising new materials or may not have access to state-of-the-art research data for these materials. How, then, can a designer perform trade-off analyses that consider novel materials or materials for which there is information limited?

Databases for Material Properties

The Army, as well as the rest of the U.S. Department of Defense, could benefit by supporting and participating in partnerships with industry and academia in assembling databases on novel materials in various stages of development and in ensuring that existing data remains accessible (confidentiality is often an issue). Cooperative programs could be established to determine data on key properties of novel materials and to enter the data into appropriate databases. Databases might be developed for electronic materials, magnetic materials, structural materials, and so on. For the structural materials database, data could be linked with processing details, fabrication scales, product forms, and probable time frames for the availability of materials for full-scale production. An entry for a new structural material might include the following information:

- material designation
- composition ranges
- fabrication history (e.g., powder metallurgy, ingot metallurgy, electron beam deposition, etc.)
- product form (e.g., extrusion, casting, rolled plate, etc.)
- scale of manufacturing (e.g., laboratory scale in 1 kg castings, pilot scale in 1,000-kg lots, full-scale production)
- mechanical properties for various orientations and product forms (e.g., yield strength, Young's modulus, fracture toughness, fatigue data, etc.)

- physical properties (e.g., coefficients of thermal expansion, mass density, specific heat, Poisson's ratio, etc.)
- chemical properties (e.g., corrosion and flammability characteristics)
- cost (relative to purchase volume) and production timelines

If a designer has access to this information early in the design process, he or she can make preliminary decisions concerning "design for reliability" or meeting the critical performance requirements for the application, as well as "design for manufacturability." The designer may determine that a novel material could be the enabling technology for a particular component or subsystem if particular property data were available within the time frame for making design decisions. Materials databases provide an important contribution to the systems engineering approach to design, materials selection, and manufacturability (NRC, 1995b).

Life-Cycle Cost Models

Materials designers must invariably make trade-offs among performance, cost, and other requirements. These trade-offs often result in compromises in materials selection and fabrication techniques. For instance, a designer working on materials for an AAN component or subsystem may need materials with high reliability as well as mechanical robustness, corrosion resistance, and wear resistance. Damage tolerance might be specified by toughness and strength. However, the higher manufacturing and acquisition costs of materials with all of these properties may make them unacceptable in designs for long-term reliability. To make rational trade-offs, design decisions should be based on *life-cycle cost* rather than acquisition cost. For example, the higher acquisition cost of a more expensive material may be justified by its reduced life-cycle costs because of its high reliability.

In addition to databases with property information, various life-cycle cost codes could be developed using today's technology to assist the designer. As the overall system becomes more sophisticated, materials costs usually decrease as a percentage of total system cost. However, selection of a superior, but more expensive, material may be hard to justify unless the potential life-cycle cost savings and performance improvements can be convincingly modeled. A readily available life-cycle cost model that could be configured for various systems would give the designer and program manager the information to justify the selection of superior materials for enhanced reliability.

Graphical Representations of Materials Properties to Support Materials Selection

From the perspective of materials engineering, a material can be characterized by a set of properties, with the value of each property falling within a characteristic range for that material. The range of values possible for just one of these engineering properties can be immense. For example, values for properties such as toughness, strength, modulus, and thermal conductivity can span five orders of magnitude. The performance requirements for a material in a component usually must be specified by more than one of these engineering properties. A simple example that is crucial for AAN systems design is the performance requirement of reducing the weight of components.

Simply looking for materials that weigh less is not the answer. What one really means by a "lightweight" material for an application is a material that satisfies the requirements for other properties, such as strength and modulus, but at a lower mass per volume (lower density) than conventional options. Thus, a "lightweight" material must really have a higher "specific strength" or "specific modulus" (the desired property relative to density) (Ashby, 1992).

Even if detailed engineering data on the properties of nonconventional materials were available to designers through materials databases, designers would still need tools for comparing them in terms of the combination of properties required for a particular design (such as the "specific" properties described above for lightweight materials). Although materials engineers have long used specific selection charts, designers need graphical tools that can tailor a chart for a set of materials or material classes that can be created from the database, similar to the way charts can be created by using a computer spreadsheet program. This is just one example of how information technology could be used to support design engineers by making materials data more comprehensible, as well as more accessible.

Failure Detection as a Performance Option

It may be more cost effective to design a self-diagnostic system that can detect impending material failure and trigger preventive maintenance than to invest in a superior material. The systems engineering approach envisioned in this report would clarify the trade-offs among these design options. Materials selection technologies should be used in conjunction with a virtual testing environment in which physical properties at a lower level of a structure or function are explicitly linked to potential failure modes at the next higher level. This is the basic principle of "physics of failure" modeling.

Modeling and Simulation Technology for Designing New or Specialized Materials

In a long-term forecast of science and technology for Army applications, the *STAR 21* study highlighted two major trends. The first was materials design through computational physics and chemistry. The second was increased use of hybrid materials, that is, materials with controlled microstructures consisting of components with different compositions (NRC, 1993a). Directions in material science since the *STAR 21* study are bringing these two trends together, which has greatly expanded the range of opportunities.

The *STAR 21* study discussed computational approaches to materials design primarily in terms of atomic-scale properties (e.g., crystal lattice effects, interatomic interactions, and molecular bonds in energetic materials and polymers). The properties of a bulk material that are determined by physicochemical interactions at this scale (measured in Angstroms, or 10-10 m) are sometimes called "intrinsic" properties. In addition to progress in analyzing and modeling how intrinsic properties arise from the atomic-scale structure of a homogeneous material, much more has been learned about bulk properties that depend on how components of the same or different materials are structured at larger scales. (The bulk properties of a material that depend on how homogeneous components of a material are put together, rather than on the intrinsic properties of these components, are sometimes called "extrinsic properties.")

Two-phase composites, in which a discontinuous phase consisting of one material is embedded in a matrix (organic, metallic, or ceramic) of another material, are relatively simple but still present a challenge to modelers. Research on materials with different structural patterns at varying spatial scales—features whose unit sizes range from microns (10^{-6} m) to nanometers (10^{-9} m)—has shown that these *hierarchically structured* materials offer an astonishing range of nonconventional combinations of bulk properties. Much of the insight into hierarchical structures originated in work on natural materials, hence the importance of biomimetic ("imitating biology") research to this area of materials engineering. Data on heterogeneous structured materials and hierarchically structured materials are particularly important to AAN needs; these materials often offer much higher values than conventional materials for "specific properties" of interest to a component or subsystem designer (e.g., combining high values for strength and toughness with low density).

The Army has been active in sponsoring and promoting research in these areas of materials science, including the current strategic research focus on biomimetic materials. Cooperative partnerships in research and application-development networks fostered by the Army Research Office, the Army Research Laboratory, and the various Army research, development, and engineering centers will continue to be productive ways for the Army to leverage science and technology resources while keeping abreast of new research and applications.

The Army should consider making two more steps to ensure a long-term contribution to meeting AAN requirements. First, as particular materials requirements for AAN system concepts are identified, they should be communicated to the materials research and application networks in which the Army participates. Better answers will be forthcoming from the materials community if the Army requirements are stated in unambiguous performance metrics. In short, AAN system designers should interact even more closely with materials researchers and developers to ensure that the Army takes advantage of new applications and materials.

Second, the Army should consider "materials by design" in terms of the emerging knowledge of how structure at all scales affects material properties.[2] The goal of modeling intrinsic properties of a bulk material based solely on the physics and chemistry of atomic-scale interactions is too simplistic for most materials that are likely to be of interest. Models must be able to simulate features at larger scales, whether random (e.g., grain size and orientation, effects of structural discontinuities during processing) or controlled structures (ranging from matrix composites to hierarchical architectures). Just as the single "mother of all models" approach failed to produce an adequate environment for designing systems through mission and system simulations (see Chapter 3), it would also be inadequate for designing materials. Both will require distributed systems that can be used iteratively to address structure-property relations at multiple levels.

[2] A significant stride in this direction will be taken if the Army approves a proposed strategic research objective on "armor materials by design" as discussed with the committee by the Army Research Office.

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Appendix D

Materials Options for Fuel Efficiency and Protection

To protect against diverse threats, such as automatic small arms, machine cannons, shaped charges and other chemical energy projectiles, as well as other weapon systems, vehicle protection systems have become very complex. Army After Next (AAN) vehicles are likely to use different types of armor to protect different areas of the vehicle, partly to reduce weight for a given amount of protection and partly to combine projectile protection with load-bearing capability. These protection system components will consist of combinations of metals, ceramics, and polymers. Enabling research to improve the building blocks of a complex armor system will provide armor designers with options for lighter combinations of materials with superior protection and structural properties to use at different locations on the vehicle to meet varying protection requirements.

One of the most controversial issues in optimizing system weight is whether and how an AAN combat vehicle should be designed to prevail in direct-fire duels analogous to "tank-on-tank" warfare. The current technology of high-velocity projectiles, such as long rod penetrators (LRPs) that can defeat even the heaviest passive armor, has raised the stakes on the protection side in the armor-antiarmor spiral.[1] For the critical mission requirements of an AAN battle force, do the tactical advantages of equipping a vehicle both to shoot these projectiles and to withstand hits from them in direct-fire (line-of-sight) combat outweigh the costs in vehicle weight?[2] The Army's answer to this question will have profound consequences for the fuel efficiency and protection characteristics of AAN combat vehicles.

According to vehicle armor engineers at the Army Research Laboratory (ARL), a vehicle that could withstand direct hits by advanced antiarmor rounds would have to weigh 45 to 50 tons, even with the best current protection technology (Havel, 1997, 1998). Based on the information available to the committee, incremental improvements in current armor technology over the next quarter century will probably not protect a 15-ton vehicle from advanced high-velocity rounds. Even if a breakthrough in active protection systems could defeat advanced projectiles, the armor to protect the crew and vehicle from projectile fragments and lesser threats, such as a machine cannon firing armor-piercing projectiles, would significantly increase vehicle weight.

[1] For an extensive technical (unclassified) discussion of the role of kinetic energy penetration in the armor-antiarmor spiral, see NRC 1993c, especially pp. 10-15 and 40-43.

[2] The weight implications include effects on vehicle mobility as well as on fuel consumption. See the discussion in Chapter 6 on gun systems and alternatives.

A strategy to circumvent this problem, at least partly, and still give the AAN battle force a capability for direct-fire engagement of opposing armored vehicles would be to remove the crew from some or most of the combat vehicles exposed to direct fire. Instead, a squad of vehicles with one or more human commanders would include unmanned vehicles operating autonomously or semi-autonomously. An unmanned vehicle could be engineered with a very low profile that would greatly reduce its vulnerability to frontal attack.[3] For offense against enemy armor, these low-profile vehicles could rely on top-defeat of opposing armor by precision-guided munitions, delivered with rocket or gun propulsion systems (see Chapter 6). Technologies for automated control systems technology and sensors may mature sufficiently in the next two decades to make this strategy practical.

In one scenario, a few manned vehicles would travel inconspicuously with the unmanned vehicles. The former would have superior protection systems at the expense of lesser armament and lethal power than the unmanned vehicles, which would be more lethally armed but would have less protection. For both the manned and unmanned vehicles in this squad, stealth technology (signature reduction, low physical profile), decoys, and agility would be major elements of a total systems approach to combined survivability and other performance objectives, including fuel economy. The best "system" approach to protection, even for protecting combat vehicles from high-energy rounds, may be to avoid being hit in the first place. Stealth, agility, better situational awareness, and longer lethal reach may become more important in AAN combat vehicles than the capability of surviving a direct hit.

In principle, an advanced active protection system is probably the best approach to shielding a 15-ton combat vehicle from multiple high-velocity projectiles or other advanced, armor-defeating rounds. A major question, though, is whether all the component technologies for such a system are feasible within the development time for an initial generation of AAN combat vehicles. The concept would need a rapid, intelligent tracking system to determine the trajectory of the incoming threat, identify the type of threat, and deploy mass or energy sufficient to deflect or reorient the projectile before it hits the vehicle. Russia has deployed a simple active protection system in which plates are propelled from the vehicle to deflect or fracture an LRP projectile. A much more sophisticated active protection system would have to be developed for a 15-ton AAN vehicle.

Materials Options for Vehicle Protection

Most of the materials now used for the building blocks in combination armors are based on mature, well characterized, but conventional technologies. Examples of conventional building-block materials include rolled homogeneous armor (RHA), which is a chromium-molybdenum steel alloy; ceramics based on alumina or silicon carbide; glass fibers; and various aluminum alloys (7039, 5083, 2519, and others).

The heavy iron-based building blocks, such as RHA, are mostly iron with a small amount of carbon and alloying elements (chromium, molybdenum, nickel, and/or silicon). They are prepared using conventional steel production methods, followed by

[3] Combat vehicles less than four feet in height are nearly immune to frontal attack from current projectile weapons on most terrain.

thermomechanical treatments to tailor the microstructure (possibly down to nanometer scale) to obtain the best combination of properties for the particular armor application.

Other building blocks include alloys based on titanium, aluminum, cobalt, or tungsten, as well as various metal-matrix or ceramic-matrix composites. Certain armor applications make use of polymer-matrix composites in which the dispersed phase in the composite may be glass, graphite (or, potentially, high-modulus carbonitrides), ceramic fibers, or whiskers of silicon carbide or silicon nitride. These building blocks are not interchangeable. They provide different combinations of properties, such as resistance to ballistic impact versus weight, structural properties, and fabrication difficulty and are suited to different applications or to different combinations in complex structural-protection architectures.

Titanium alloys, by virtue of their high specific strength (strength per unit mass), are promising building block materials for lightweight armor on combat vehicles. However, their susceptibility to spalling requires the extensive use of spall liners or other techniques, which reduces the potential for weight reduction (Thompson, 1998). Curiously, the leading titanium alloy in current armor applications is Ti-6A1-4V, which has been the mainstay titanium alloy for many uses since the early 1960s. The committee was unable to determine whether this alloy is objectively superior to newer titanium alloys for armor applications or whether it was selected for its greater production history. Advanced titanium alloys, which are being evaluated by the ARL, may warrant development specifically for their superior protection properties, particularly if a composition and temper with superior ballistics characteristics and other advantages can be developed.

The history of advanced titanium alloys illustrates some of the common obstacles to the widespread acceptance of many advanced materials. Difficulties in processing have added to the cost of these materials and their low fabrication reliability (high rejection rate). Alternative processes, such as the electroslag remelting process developed in the former Soviet Union for advanced titanium alloys, will be necessary to improve manufacturability and lower the cost for these and other innovative building-block materials. The electroslag process yields high-quality rectangular ingots that can be rolled to armor plate gauges. By contrast, the conventional round ingots from vacuum-arc-remelting require expensive forging operations to shape them into rectangles before they can be rolled into plate. For titanium bar products, which might be used in structural members supporting armor plate, the plasma coal hearth process would allow casting closer to final thickness, thereby reducing costs for hot-working the castings. In addition to exploring lower cost processes, the minimum purity of an alloy that would provide adequate ballistic protection, including resistance to spalling, should be identified. Materials engineering teams will have to work concurrently on issues of availability, manufacturability, and reliability, in order to realize the multifunctional benefits (e.g., same or better protection at reduced system weight) of advanced materials.

For scout vehicles or aircraft, where weight reduction is critical and protection requirements are less demanding, aluminum lithium alloys have promising potential for combined structural-protection advantages. Some of these high-strength lightweight alloys, such as 2195 and 2094, which were developed for the space program, have extremely high specific strength and toughness. The Army could leverage NASA's substantial investment in engineering and manufacturing development.

To date, research on ordered intermetallics has not yielded strength-toughness combinations approaching those of the chromium molybdenum steels or titanium alloys, such as Ti-6A1-4V. However, modest progress has been made with the iron aluminide and titanium aluminide intermetallics, which may provide lighter weight alternatives to the currently accepted options.

Ceramics with increased resistance to ballistic penetration are also options for the building blocks in vehicle protection systems. One expert noted that the Army' s reliance on large, costly empirical test matrices reflects an incomplete understanding of the defeat mechanisms of ceramic armor materials (Thompson, 1998). This is an area in which modeling could help meet AAN survivability goals for a 15-ton vehicle. An expert at the ARL, who agreed with the general need for modeling, emphasized that current materials models and computer codes cannot simulate the wide range of candidates for metallic and ceramic materials in protection systems (Havel, 1998).

Current ceramics options with good ballistic penetration resistance per unit mass include TiB_2 and B_4C. Unfortunately, they are both expensive because of their boron content and relatively limited production volumes. In addition, hot pressed or hot isostatically pressed ceramics of a given composition generally perform better than less expensive sintered ceramics. Research on new processing methods will be necessary to reduce the cost of high-performance ceramics of a given composition. According to an armor specialist at the ARL, new ceramic materials suitable for armor applications may either remain undeveloped or fail to make the transition to affordable production unless parallel commercial applications are found (Gooch, 1998). At current funding levels, successful commercial application will be necessary to drive development and production scaling.

The 15-ton weight desired for AAN ground combat vehicles, coupled with constraints on transport volume, will require protection structures with good mass efficiency (protection per unit mass) and volume efficiency (protection per unit volume). These generally conflicting, and therefore challenging, requirements could possibly be achieved by ceramics or ceramic-rich metal composites, such as tungsten carbide, which possesses exceptional volume efficiency, or functionally graded ceramic-metal composites (Gooch, 1998). Ceramic-metal composites with simple architectures (three-dimensional interpenetrating structures and laminates) are being developed to combine the toughness of the armor metals with the hardness of ceramics. Composites containing borides, carbides, or nitrides, many of which have not been fully evaluated because of cost and scale-up issues, may also prove to be useful in components of vehicle protection systems (Thompson, 1998).

Functionally graded materials, including intermetallics and ceramic-metallic composites, have demonstrated excellent protection characteristics in bench-scale testing of tiles. However, engineering development of promising candidates will be necessary to explore their performance in a system. In addition, the processing methods used to produce the prototype materials are too costly, for the reasons mentioned above for titanium alloys. To bring down the cost and ensure the availability of structural components, processing methods, manufacturing and fabrication quality control, and finishing techniques will have to be improved.

New Architectures for Protection System Components

Among the new scenarios for protection systems are (1) reactive armors that include systems with a surface layer of an explosive material that can counteract the force of the incoming projectile; (2) active protection systems that can detect the projectile and eject a plate or shot that can stop it away from the surface of the vehicle;

(3) smart armors that can detect incoming projectiles and assess the damage they cause; (4) electromagnetic armor (or shielding); (5) surface geometries that can deflect projectiles and reduce the effects of impact; and (6) systems that incorporate stealth technologies that can reduce the vehicle' s electronic or thermal signature or alter its visible profile (making it harder to identify and target). New candidates for protection system components also include architectural concepts borrowed from natural biological systems that have evolved to absorb substantial amounts of kinetic energy from impact without catastrophic failure. Some of these concepts involve stopping projectiles without the brute protection characteristic of conventional passive armor materials. "Dynamic" materials could be developed that could change properties when they are hit to absorb significant amounts of energy by altering their lattice structure, their architecture at the micrometer and nanometer scales, their defect structure, or their bulk volume or shape.

Processing and Fabrication Technologies

Along with developing new materials options for building blocks and new architectural concepts to use them, new cost-effective processing and fabrication technologies will be necessary to keep protection system components affordable and available. Research in new processing technologies, including technologies that can produce structures with nanometer-thick, ordered layers (nanostructures) of intermetallics, ceramics, and metals, could provide major breakthroughs in the next decade. Research on processing technologies that can produce scale-specific structures could lead to novel architectures in which ordered intermetallics, ceramics, and metals would form distinct structural patterns at different scales.

A critical issue for the production of functionally graded or nanostructured armor materials is that processing technologies must be cost effective and amenable to scaling. Electron beam deposition, laser processing, and various thermal deposition processes might be further developed to produce finely layered or functionally layered components from these materials.

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Appendix E

Duty Cycles and Fuel Economy of Hybrid Vehicles

The section on Hybrid Vehicles in Chapter 4 raises the issue of whether a hybrid combat vehicle would have better fuel economy than a vehicle with a conventional mechanical power plant (e.g., a diesel or turbine engine without the electrical conversion and storage subsystem of a hybrid) for "AAN-like" duty cycles. This appendix cannot answer the question, but it does explain in more technical detail the reasons why the committee believes the Army should make complete engineering assessments before making design decisions.

A hybrid-electric power plant reduces fuel consumption principally because the engine runs more of the time at or near peak efficiency, rather than at lower engine speeds where the engine is less efficient at converting stored energy in the fuel to mechanical energy in the driveshaft. In addition, if the hybrid system uses electrical motors at the drive wheels as electrical generators during vehicle braking, some of the kinetic energy of the vehicle's motion can be recaptured and stored (regenerative braking). By running the engine at near peak efficiency and storing the extra energy during off-peak demand phases of the duty cycle (and by storing the energy captured during regenerative braking), the electrical subsystem can provide the energy required during peak power demand phases of the duty cycle (acceleration, climbing hills, etc.). If the duty cycle includes enough off-peak (and braking) time to keep the electrical storage component energized, then a smaller engine can be installed, which is how fuel economy is improved. Ideally, the engine would be sized so that it runs constantly near its maximum rated continuous speed, where it is most efficient, because storage capacity for excess engine power output over vehicle power demand is always available. The mean power demand of the duty cycle, however, must be much lower than the rating of the engine for maximum sustained power output.

Figure E-1 shows the duty cycle for a vehicle weighing 3.4 metric tons (7,500 lb.) with an engine rated at 235 brake horsepower and a maximum torque of 440 ft-lb. The figure shows the percentage of time during the duty cycle that the engine operates within nine ranges of engine speed and seven ranges of torque. (Power equals engine speed times torque.) This duty cycle approximates that of a city bus making frequent stops along its route. Note that torques greater than 250 ft-lb. (the back row of cells) only occur during a very small percentage of the duty cycle. The cells representing most of the duty cycle are clustered toward the front left of the diagram at low-to-medium engine speeds and low torque. The average power, for two different driving conditions, ranges from 14.5 to 15.4 brake horsepower, or about 15 percent of the engine's rated power. This duty cycle is a good candidate for a hybrid vehicle. Applications like this one are the source of the rule of thumb that, to consider a hybrid-electric power plant for reasons of fuel economy, the average power demand in the duty cycle should be one-fifth or less of the peak demand.

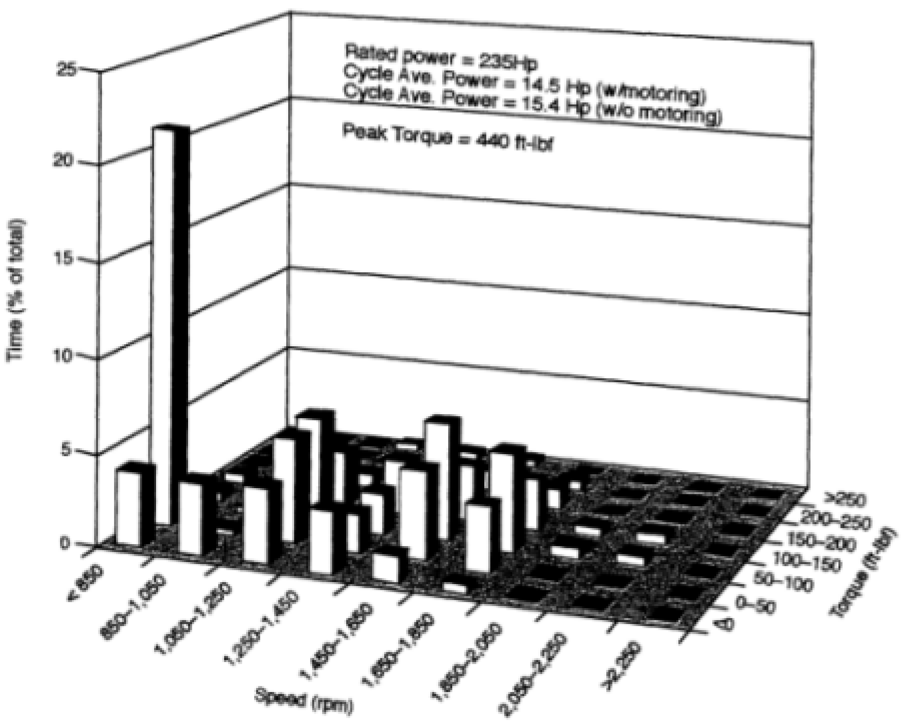

Figure E-1
Duty cycle for a 3.4 metric-ton vehicle with an engine rated at 235 brake horsepower and a maximum torque of 440 ft-lb.

Appendix F

Situational Awareness

This appendix provides background information on the committee's assessment of situational awareness (SA) technologies. The importance of SA on the battlefield of the next century cannot be overstated. Having accurate information (such as friendly and enemy locations, maps or images of local terrain, processed intelligence regarding opposing forces, weapons, and activities) has been uppermost in the minds of military commanders since the days of semaphores and rudimentary battlefield communications. Technology can make all of this and more possible for the Army After Next (AAN). Advanced satellite and observation systems, as well as sensors and location devices, will operate in a network "global grid" that provides secure, high bandwidth, high throughput communications capabilities. Widespread, diverse sensor arrays, communications links, encryption, and computers will work together to provide relevant intelligence data for near-perfect and near real-time SA to the AAN force commander.

SA and information dominance will be fundamental to the success of the AAN battle force. Perfect, or near-perfect, real-time SA will help to minimize the impact of AAN logistics burdens. Accurate knowledge of enemy locations and capabilities and precision targeting with high kill probabilities will minimize the weight and volume of the ammunition burden. Perhaps even more significant, with accurate planning and operational information enabled by SA, the AAN will be able to insert a right-size force with the right suite of weapons and equipment at the right place and time. This "right sizing" of the force will determine in advance the optimum number of soldiers, weapons, armor protection, numbers of vehicles, fuel requirements, and overall deployment weight of the force.

Although modernization through "digitization" of the battlefield is an important goal for Army XXI, the information capabilities gained will not reduce the need for research and development in SA technologies. The committee believes that research and development programs in the technology areas discussed in this appendix will be vital. Information technology is changing faster, and much more significantly, than any other aspect of the AAN scenario. The committee believes that rapid progress in the technological foundations for information dominance will continue into the AAN time frame. Relevant enabling technologies include electronic and photonic devices; integrated circuits; microprocessors, processors, and firmware logic; software (computing instructions); communications hardware and information transmission algorithms; complex system and network design, integration, and management.

Progress will not be uniform for any particular technology. As a technology matures, the rate of progress will eventually decrease, although ongoing innovations make the time of maturation impossible to predict. When a maturing technology is replaced through radical innovation, rapid growth may resume in capabilities based on the innovation, or entirely new capabilities may appear. In short, although overall progress can be expected, predictions of the trajectories of particular SA capabilities for even five or ten years are unreliable.

Therefore, it would be dangerous for the Army to expect to maintain information dominance in 2025 by relying either on the continuation of a current trend in a particular technology or on the prediction of a technological limit to the improvement of an SA capability. The committee is concerned that AAN planners may assume that incorporating today's (or even tomorrow's) information technologies into Army XXI systems (around 2010) will ensure full SA and information dominance for AAN (in 2025). The Army must continue to make substantial efforts to follow and incorporate state-of-the-art developments in SA technologies (in AAN terminology, improve "mental agility"), at the same time as other aspects of force enhancement ("physical agility") become the focus of AAN systems development efforts.

One important consequence of rapid but unpredictable growth in SA technologies is the necessity for constant reassessments of the consequences of unanticipated SA advances (or a lack of expected progress) on AAN operational concepts and systems design. The modeling and simulation (M&S) environments described in the body of this report should include simulations of the impact of alternative levels of SA capability on particular systems or operations (engagements). Simulations to support major decisions on design, development, or reengineering should include sensitivity studies that model the effects of incremental increases or decreases in SA capabilities. These simulations should also be used to provide insight on how the loss or severe degradation of an SA capability (through component failure or hostile countermeasures) would affect system functions and operational outcomes.

The hardware for both communications and computing will come mostly from commercial sources; the Army should concentrate on unique applications of commercial technologies. Information gathering will be done by a wide range of sensors (e.g., electromagnetic sensors, [ultraviolet, visible, infrared and millimeter wavelengths], acoustic sensors, and chemical biological warfare sensors) configured in unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), multipoint fixed arrays, and manned vehicles. This information will have to be communicated back to the command center.

To reduce the communication demands of increasingly capable sensors, local intelligence will be incorporated at the sensor to preprocess the data and reduce bandwidth requirements for transmission. A single multispectral (5 bands), real-time (60 frames/s), high-resolution (2000 x 2000 pixels) video signal could require as much as 600 MB/s bandwidth. The volume of data to be processed will require sophisticated computation for automated analysis and semi-automated decision making and rapid response. After target acquisition, decisions must be communicated to the appropriate weapon platform. Supply units must be updated on ammunition supplies. Sensor feedback on battle damage must be assessed and intelligence data updated.

Figure 6-1 is a schematic representation of the components of this SA system. All of the computation requirements (at the sensors, at the distributed command and control nodes, and at the response platforms) will need more robust software than is currently required to perform mission-critical functions. An opponent skilled in camouflage and deception could defeat a totally computerized system (as well as human observers who do not actually make physical contact, such as those looking at remote videos).

The communications links will have to be exceptionally robust. Large amounts of data will have to be transmitted securely and reliably over a complex and rapidly changing network in the face of enemy attempts at disruption and dis-information. This system will be vital to the success of a numerically inferior force that will have to operate swiftly and effectively at a significant distance from its base.

This appendix discusses technologies that are vital to ensuring unequivocal lethality including: sensors, communications, ground positioning, computers, and battlefield management. Some of these are treated with less depth than the others because information about them is classified and was not available to the committee. As long as these technologies are on a trajectory that will continue into the AAN acquisition time frame, the Army must not assume that the job is done and turn its attention away from the underlying silicon technologies.

The SA battlefield environment can provide complete, real-time, and near perfect knowledge of the battlefield. The SA environment will provide detailed, accurate location information for friendly, allied, or coalition forces, as well as for opposing forces. It will also provide planning information for course of action analyses and mission planning of battle force operations. The SA environment described here will also be a fundamental tool for reducing ammunition, force size, and armor and vehicle loading and will enable the shift from "just in case" logistics to "just enough" logistics.

Sensors

The AAN will use a wide range of sensor technologies, ranging from highly sophisticated focal-plane arrays to single-point chemical sensors, perhaps on widely dispersed networks. Prognostic sensors will provide information on readiness. Ambient sensors will provide detailed mapping of local environmental conditions. Threat sensors will detect enemy forces in highly cluttered environments. Target sensors will designate targets and provide guidance information.

Combat Threat Detection

In broad terms, the objective of these sensors is to detect and identify targets in cluttered environments at the greatest possible distances. This will require not only enhanced sensors but also signal processing and artificial intelligence that can extract useful information from the mass of available data. Sensors will be both passive (e.g., detecting differences in emissions between the target and the background over multiple spectral ranges) and active (e.g., laser detection and ranging and radio detection and ranging [LADAR/RADAR]).

Current research programs are addressing multiple aspects of these sensor systems, including high-resolution, staring focal-plane arrays that are sensitive over multiple spectral ranges (including millimeter-wave, infrared, visible, and ultraviolet spectral regions); local networking links that can transfer data from multiple focal planes to a central processor for data fusion; and advanced signal processing that can extract useful information from the mass of data. Advances in complex semiconductors and processing will be necessary to fabricate these devices. In particular, infrared sensors will require multilayer compound semiconductor structures that can be tightly integrated with silicon processors.

Current research is focused on a number of material systems, including InGaAs quantum-well infrared photodetectors and HgCdTe systems. A critical issue in each of these is the speed of data transfer from the compound semiconductor to the silicon processor. Both highly parallel optical interconnects and heterogeneous material integration (e.g., wafer bonding of the focal plane array and the silicon electronics) are being actively investigated.

Advances in the scale of electronic devices are making it possible to integrate much more processing locally (e.g., within a pixel and between adjacent pixels). Emphasis on automatic target recognition (ATR) signal processing capabilities will become increasingly important as the number of sensors increases and their capabilities improve. The closer to the sensor ATR can be done, the lower the demands on communications resources.

In parallel with the development of these highly capable imaging sensors is the development of a distributed network of inexpensive sensors. The Defense Advanced Research Projects Agency (DARPA) is working on the development of a network of randomly distributed, acoustic sensors that can communicate via a low-bandwidth wireless radio frequency net. A major attribute of this network is the relatively low cost of each individual sensor, which would make highly redundant distribution affordable. Thus, only a small subset of the total distribution network would have to be working. The signal processing and communications requirements for this kind of redundant, dynamically reconfigurable distributed network are very different from those of expensive, hyperspectral focal plane array sensors. Even though the fusion of data sets from different sources has been under investigation for more than 20 years in the Beta Test Beta program and other data fusion programs for intelligence and sensor data, accelerating advances in sensor technology require new insights into data fusion for the optimal extraction of information.

Distributed Threat Detection

Chemical and biological agents are growing threats, particularly for the asymmetric confrontations anticipated for the AAN. The problem is exacerbated because protective measures tend to be uncomfortable and to restrict war-fighters' capabilities in terms of vision, mobility, and reaction. Protective gear will only be used at all if there is a reliable advance detection and warning of chemical and biological agents.

Current technologies for building microminiature chemical and biological processors that can combine chemically or biologically specific surfaces with electronics and optics using simple forms of micromachining are still rudimentary. Chemical sensing micromachines have been used for miniature gas chromatography and ion-trap mass spectroscopy. Selective surfaces include reactive metals (e.g., Pd for sensing H2 as the gate metal for a silicon field effect transistor) and biologically specific adsorbents for optical sensors (e.g., surface plasmon resonance devices). These are currently very active areas of research, and major advances in the capabilities of these devices can be expected by the AAN time frame.

All of these local devices will have to be networked to provide broad coverage and advanced warning. If they are integrated into UGVs for use in different locations, they would increase complexities in terms of distribution, communications, and signal processing. On the other hand, if advances in sensor processor technology follow the path of advances in semiconductor technology, sensor processors are likely to be very small and very inexpensive, which could result in affordable networks that are highly redundant, fault-tolerant, and difficult to disrupt.

Environmental Sensors

Terrain. An extended terrain database will be necessary for the AAN to achieve high-speed mobility and to engage the enemy effectively. Real-time mapping and data storage will be necessary to provide the SA capability before and during hostilities. Mapping information should be provided to the force in a retrievable electronic form, rather than adding to the already difficult communications burdens. The very high-density storage devices, high-resolution displays, and software to accommodate this information are likely to be developed by the commercial sector. Therefore, the Army should concentrate on ensuring reliable, high-resolution terrain data. The National Imagery and Mapping Agency (NIMA) is responsible for coordinating all government activities in this area (see Chapter 5 for discussion of AAN terrain database requirements to support mobility modeling).

Weather. Weather sensors should provide a three-dimensional, high-resolution description of the local weather, including wind conditions, to optimize performance of projectile weapons systems. Local weather data will probably be provided by UAVs.

Prognostics. Prognostic sensors can be valuable for maintaining equipment and ensuring the readiness of combat systems, vehicles, and soldiers. Large-scale applications of prognostic sensors will most likely be driven more by the commercial sector than by the relatively small military market. Considering the short-duration AAN scenario, the committee believes that "mission reliability" is a better approach to ensuring the availability of resources for the AAN (see Chapter 7).

Computers

Computers are, and will continue to be, the heart of weapon systems and other combat-related systems. Therefore, they will also be essential to reducing logistic burdens. Although commercial developers will provide most of the hardware tools, the Army will have to ensure stable, secure, user-friendly, timely information and options analysis for a battle force on the move. Computer technologies are closely related to communications, as well as to data acquisition and sensors, ground positioning, battlefield management, guidance control, and supply. Computers will permeate AAN systems. The committee agrees with the recommendation of an earlier NRC report, Energy Efficient Technologies for the Dismounted Soldier (NRC, 1997a), that it may be inappropriate for the Army to distribute ruggedized versions of personal computers to every soldier. This would, of course, increase the soldier's load and add to the soldier's logistics burden.

Just as modern industry is unthinkable without computers and tied-in communications, warfare in the twenty-first century will be unthinkable without applying information technology to the projection of force. The very large commercial market drivers pacing the changes in information technology are unique to this technology area. Looking back 35 years gives one a perspective on the changes that have been made, from slide rules and mechanical calculators to laptop computers and from rotary dial handsets to cellular connections to the Internet. The Army cannot make a static, one-time decision to adopt information technology, because the dynamic, constantly changing environment of information technology will continue after Army XXI becomes a reality.

In the near-term, computers will have a direct impact on logistics by improving inventory control and resupply efficiency (just-enough logistics and "end-to-end asset visibility") through improved information flow and tighter management. In the future, predictive and diagnostic sensors could conceivably be linked with the information network to ensure that proper repair and maintenance supplies are available. Even though the relatively short duration of AAN missions will minimize the utility of predictive and diagnostic sensors on the battlefield, the sensor information will still be of high value to the Army as the basis for system analyses.

Portable computers will be a major consumer of battery power. Because this will also be a problem for commercial computers, industry will probably address it. The Army should have an advantage for supplying power because chargers in vehicles should be easily available. Servers may require cooling, even if they are small, which will be a more significant problem for the Army than for commercial users, who are not required to operate in extreme outdoor environments. The Army has acknowledged that the cooling of electronic equipment is a growing problem, particularly in enclosed combat vehicles. In fact, a thermal management system (i.e., air conditioning) is presently being investigated for the M1A2 main battle tank to protect the electronics and crew from overheating.

Long-term logistics issues associated with maintaining and upgrading both hardware and software systems will have to be addressed. Because of rapid evolution in both areas, it will be a challenge for the Army to maintain an integrated system across all of the evolving platforms. Both hardware and software upgrades will have to be implemented in planned stages so that applications programs can be developed in good time. The cost of continually updating computers and software will be substantial, especially if the current rate of change continues for the next 30 years.

Computer hardware and software for AAN field use must be reliable and stable (physically rugged and not subject to software glitches). It must also be user friendly because users will be under significant stress. Computers should not contribute to information "overload," and computer networks must be redundant enough to sustain combat losses of individual servers and communications links.

Current research on hardware is dominated by commercial requirements. The Army cannot count on the commercial sector, however, to provide reliable enough hardware to meet military requirements for ruggedness, bulk, and display resolution. The commercial goal of replacing disk drives with solid-state memories with sufficient capacity for limited tasks might improve ruggedness, but the commercial sector will only address military concerns coincidentally. The Army's cost for the development of acceptable computers may be high because the economies of scale in the commercial market will not apply to the small numbers of computers needed by the Army.

Other uncertainties about SA technologies are common to both commercial and Army (military) applications, although the appropriate responses to these uncertainties may differ for military and commercial-market planners. A good example of the unpredictability of progress in a key enabling technology is the significant debate as to how much longer Moore's Law will continue to hold.[1] There is general agreement that capacity will increase by at least one to, possibly, three orders of magnitude (10 to 1,000 times the capacity of 1998 technology) by 2025. Among the points at issue are how long the historical growth trend in functional capacity can be sustained and how quickly the improvement rate will drop for silicon-based semiconductor technology.

So far, the manufacturing improvements responsible for sustaining this exponential trend have been based on scaling down device parameters such as silicon oxide thickness, doping, and gate length, while continuing to use silicon as the semiconductor material. This scaling can probably continue to gate lengths of around 50 nm. Experimental transistors and circuits with 50-nm gate lengths have been demonstrated. For comparison, Intel is now producing 250-nm gate lengths and is moving towards production based on a 180-nm gate length. The U.S. semiconductor industry currently projects that performance improvements *in production manufacturing* will fall below a Moore's Law extrapolation by a factor of two in 2006 (SIA, 1997). Yet even this performance assumes that transistors can be manufactured with a silicon oxide thickness of about 2 nm.

Currently, when the oxide thickness is below 10 nm, current leakage increases because of direct tunneling, a fundamental characteristic derived from the quantum properties of atomic-scale phenomena. To prevent a destructive buildup of heat from this leakage, the voltage across the oxide layer would have to be reduced from the present 3.3 volts to about 0.5 volt for a chip with a billion devices. The industry road map projects a reduction to about 1 volt, which would require a significant compensating loss in performance to avoid the heating problem. In addition, there are significant concerns that current through the oxide even at this level will seriously detract from the reliability of the devices (Okada et al., 1998).

Even before the decrease in oxide layer thickness begins to be an obstacle, other problems may impede improvements in microprocessor performance. Thermal loads and both intra- and inter-chip interconnect performance are major outstanding issues that also threaten to slow the advance of silicon technology.

Approaches to mitigating various problems are being developed, such as reducing voltage requirements by decreasing operating speed or using silicon-oninsulator technology. Active cooling may allow some more development, but it is not known at this time how much. Moreover, cooling requires energy. Thus far, these mitigating options are one-time improvements that do not constitute a radically different technology trajectory. Nanotechnology (e.g., single-electron Coulomb blockade

[1] Moore's Law is an empirical generalization first stated in 1965 by Gordon Moore, then the chairman of Intel Corporation. Moore observed that a graph of the growth of memory chip capacity (measured in numbers of transistors per chip or millions of instructions executed per second [MIPS] approximated an exponential growth curve with a doubling time of one year. Since then, growth has slowed, and the period for doubling microprocessor capacity is now usually given as 18 months (Intel, 1998; Ziff-Davis, 1998). Intel describes Moore's generalization for memory chips as having a period of 18 to 24 months (Intel, 1998). In September 1997, Moore pointed out that the physical limits of silicon technology would put a limit on the ability of the semiconductor industry to continue the Moore's Law trend in manufacturing improvements. Moore also said that power consumption and the resulting heat will be an enormous challenge long before the physical limit on transistor size is reached (Kanellos, 1997).

transistors and cellular automata architectures) is being explored with the hope that it might provide an alternative to the traditional metal-oxide semiconductor transistor technology as the latter reaches fundamental limits. To date, none of these approaches appears likely to surpass the functionality provided by mainstream silicon technology.

In summary, although some improvements in performance will continue beyond the next decade, they will probably not be achieved by continued scaling down of transistor size at the historic Moore's Law rate. For critical operations (including many Army applications), trade-offs among performance characteristics, such as processing speed, size, and reliability, at the circuit and component levels will have to be assessed. Reliability standards that are acceptable for mass-market commercial applications may be unacceptable for Army SA systems.

Software is also a serious problem. Windows, the operating system used in most small computers, is notably unstable, especially when used for multitasking. OS/2 is better, but less user friendly. UNIX-based systems are still better but are not notably user friendly. It is not yet clear what the stability of Windows 98 or Windows NT will be although the latter is a distinct improvement over Windows 95 and might be as stable as UNIX. Neither compares with mainframe operating systems, however, in terms of stability and reliability. Because the requirements for stability on the battlefield exceed those of personal users and even of most commercial users like banks, insurance companies and airlines, there may not be a demand for extremely stable systems that are user friendly in the commercial arena. The task of development would, therefore, be left to the military.

The closest match to military requirements may be the requirements for reliability of the air traffic control system, although the military will require far more redundancy and operate in a much more chaotic environment. The military network must be capable of being broken up into smaller networks if the reliability of the larger network becomes suspect. This will reduce vulnerability to attack and facilitate reconstitution and recoverability.

Another difference between commercial and military networks is that the military command network must be hierarchical while other military networks, such as the indirect fire support network that responds to targets of opportunity, must be less hierarchical. It is doubtful that a single commercial architecture could efficiently handle both.

The Army also must resolve significant issues related to software complexity and adaptability. The AAN will require a very complex software overlay for handling intelligence that will receive terabits of information from a large number of sources in a rapidly changing environment and distill the information for users as diverse as commanders and autonomous platforms. Fundamental questions must be answered about the limits of robustness and stability in such a system.

Security problems for commercial and military computers are similar in some respects but different in others. The short time of each AAN engagement will reduce the vulnerability of field ciphers but the number of engagements will increase it. Most military studies of cryptography and security have been done by the Army in conjunction with the National Security Agency (NSA). A new generation of "Fastlane" encryption technology, which has been developed to accommodate the speed, volume, and bandwidth needed by the National Reconnaissance Office (NRO), when coupled with asynchronous transfer mode (ATM) communications links and a centralized key management system, will go a long way toward solving the security problems that will be encountered in the AAN time frame. Because most information on security issues and technologies is classified, the committee can only reiterate the general seriousness of security considerations.

Display (Soldier-Computer Interface)

Unless we give over the battlefield to computers and robots, the Army will have to devote a good deal of attention to the final communications link between the computer and the human brain. This is both a hardware and a software issue. Display hardware will have to be improved in resolution, robustness, and portability. The needs of the force commander, of mounted soldiers, and of dismounted soldiers are very different. Dismounted soldiers will need lightweight, heads-up displays that provide information without restricting their peripheral vision.

Many active software programs that can visualize complex data (e.g., virtual reality, graphic presentations of databases, three-dimensional modeling) simplify data presentation but incur large costs in computational resources and in time. Much more work will be required to make timely information available in a form that is more suited to humans than computers.

Although the sense of sight is the most information rich of all human senses, in some situations, auditory or other sensory inputs may be more efficient and less distracting. The Army should investigate interfaces that involve all of the human senses.

Communications

Although radio communications systems and the global positioning system (GPS) are vulnerable to jamming, the committee found little evidence that the Army takes the threat of enemy jamming seriously. In tactical war games and field problems, opposing forces are usually prohibited from jamming. Eventually, this policy could prove to be disastrous, especially to an AAN battle force that will be entirely dependent on massive data transfer. Even though electronic warfare technologies are classified and this discussion was limited, the committee believes that jamming poses a significant threat to the AAN.

A very large aggregate bandwidth will be necessary to transmit detailed, high-resolution, real-time, multispectral mapping/imaging and threat identification to a changing battlefield with a large number of nodes with radio frequency links. Current and follow-on technologies being developed by the National Security Agency (NSA) and the National Reconnaissance Office (NRO) initiatives (Fastlane encryption and ATM networks) are expected to resolve some of the throughput and bandwidth problems before the AAN time frame, but bandwidth requirements will continue to expand. A shift to millimeter-wave links will be necessary, even if terrain information is loaded prior to battle. Broad-band communication will be critical and could be vulnerable if airborne relays are required.

The communication network needed for the AAN will include many sources of very large amounts of data, many nodes trying to access information, many redundant communications channels (e.g., radio frequency, microwave, optical, earthbound, UAV, and satellite) to ensure connectivity, and many protocols (e.g., encryption, spread spectrum, frequency hopping, code division multiplex) to ensure authenticity and increase aggregate bandwidth. Network management in such a complex environment will require robust software to ensure that the system can operate reliably under high-stress battlefield conditions. Commercial systems are based on the highly democratic Internet protocol (i.e., the system slows down as more users demand access). A military system must have a more hierarchical structure based on dynamic prioritization. The commander will need a continuous overview. A sensor that detects an incoming threat must be able to get its message across. This is a complex problem that will be very difficult to solve.

Neither a detailed analysis of the bandwidth requirements associated with an AAN battle force nor a mapping of bandwidth requirements into available resources was discussed with the committee, which therefore assumed that the Army is not yet working on battle force communications issues. If this assumption is correct, the committee recommends that the Army coordinate its development plan with NSA and NRO initiatives. The Army should have an ongoing assessment of communication requirements and a planning process either to accommodate them or reduce them.

Vulnerability

The flip side of self-reliance is dependency. Information technologies (e.g., sensors, computers, artificial intelligence, and communications) are essential to SA, which in turn is essential to AAN battle force systems. At the same time, information technologies can increase the battle force's vulnerability. The SA system for the AAN will be one of the most complex, dynamic, interwoven systems ever produced. Failures could arise from errors in the fabric of the system that are revealed only by the stress of the battlefield, from hardware failures, or from enemy attempts to disable or misinform them.

The year 2000 software problem is an object lesson in the difficulties of providing truly robust software for complex systems. A software decision made many years ago when computer memory was in short supply to use only two digits to encode the year (e.g., 65 for 1965) has necessitated major expenditures of time and money as 2000 approaches. This was a predictable problem, but systems designers in 1965 (or even 1990) did not anticipate that the code would still be in use in 2000.

Complex code can also have hidden software errors. Many large complex commercial systems (e.g., the extended failure of AT&T long distance telecommunications computers in 1996) have gone out of service because of unforeseen combinations of circumstances that caused the software to crash. Everyone who uses the Windows'95 operating system on a personal computer has experienced system crashes. These crashes may be annoying, but they are not serious because they can be corrected by rebooting the computer and reentering material that had not been saved.

The network software for AAN will be vastly more complex, will have to be dynamic to accommodate rapidly changing circumstances, and will undoubtedly be tested in unforeseen ways by battlefield stresses. A failure that requires the equivalent of rebooting the system would be clearly unacceptable. The Army will have to apply a rigorous testing and evaluation program not only to eliminate as many vulnerabilities as possible, but also to ensure a graceful failure that can rapidly shed problems (both software and hardware) without bringing the entire system to a halt. This will be a major software challenge.

Hardware reliability and hardening are other issues that must be addressed. First, redundancy will be essential (e.g., the Internet provides multiple routing options and does not depend on a single communications link). Second, electronics can be vulnerable to high-power electromagnetic radiation. Unfortunately, this vulnerability has increased with the increasing numbers of transistor-based devices used in advanced microelectronics. Third, the Army will have to protect electronics against attack. This is a more serious issue for nodes and command centers where there are concentrations of electronics than for distributed, redundant sensor networks.

Enemies have always attempted to exploit vulnerabilities in the SA system to improve their battlefield situations. As technology has advanced, methods of protecting information have not always kept pace. Increasing functionality is often more exciting (and more fundable) than ensuring its security and authenticity. As certain technologies become available routinely, both sides will probably achieve parity; an opponent who has no installed system could even have advantages over a larger force with installed systems that are expensive to update or replace. The Army will have to guard against these twin dangers as technology develops into the AAN time frame.

Existing Programs

The Army has significant research focus under the battlefield communications strategic research objective (SRO). The Army Research Laboratory is working in integrated teams with university and industry laboratories, computer networks, automated target recognition, and wideband communications. Many of these programs are predicated on the maximum use of commercial hardware and software. If rigorous field and operational testing should show that commercial equipment and systems are inadequate for the AAN, the scope of the research projects will have to be increased.

All of the services and DARPA have large research programs on sensor technologies. The Air Force is working on electro-optics for both air-based and space-based reconnaissance and is investing heavily in UAV technology. DARPA has extensive programs in forward-looking infrared sensors. The Navy has several university initiatives in chemical/biological warfare sensors. National laboratories, including Sandia, Livermore, Argonne, and Oak Ridge, are working on various aspects of sensor, communications, and computer technologies that are relevant to the AAN. The committee was not convinced, however, that these programs and projects are well coordinated.

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