
# 2009-2010 Assessment of the Army Research Laboratory

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# Assessment of the Army Research Laboratory

Army Research Laboratory Technical Assessment Board

Laboratory Assessments Board

Division on Engineering and Physical Sciences

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This report has been reviewed in draft form 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 institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Alton D. Slay, Warrenton, Virginia. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring board and the institution.

# Contents

# Summary

The charge of the Army Research Laboratory Technical Assessment Board (ARLTAB) is to provide biennial assessments of the scientific and technical quality of the research, development, and analysis programs at the Army Research Laboratory (ARL). The advice provided in this report focuses on technical rather than programmatic considerations.

The Board is assisted by six National Research Council (NRC) panels, each of which focuses on the portion of the ARL program conducted by one of ARL's six directorates. When requested to do so by ARL, the Board also examines work that cuts across the directorates.

The Board has been performing assessments of ARL since 1996. The current report summarizes its findings for the 2009-2010 period, during which 96 volunteer experts in fields of science and engineering participated in the following activities: visiting ARL annually, receiving formal presentations of technical work, examining facilities, engaging in technical discussions with ARL staff, and reviewing ARL technical materials.

The Board continues to be impressed by the overall quality of ARL's technical staff and their work and applauds ARL for its clear, passionate concern for the end user of its technology—the soldier in the field—and for ARL's demonstrated mindfulness of the importance of transitioning technology to support immediate and longer-term Army needs.

ARL staff also continue to expand their involvement with the wider scientific and engineering community. This involvement includes monitoring relevant developments elsewhere, engaging in significant collaborative work (including the Collaborative Technology Alliances [CTAs], International Technology Alliance, University Affiliated Research Centers, and University Centers of Excellence), and sharing work through peer reviews (although the sensitive nature of ARL work increasingly presents challenges to such sharing).

In general, ARL is working very well within an appropriate research and development (R&D) niche and has been demonstrating significant accomplishments. Examples among many include the following:

- Advances in deployable facilities for the machine translation of foreign-language material in ways that are clearly relevant to real Army problems; new work that has combined ARL's strengths in both quantum physics and advanced high-performance computing to perform first-in-the-world demonstrations for what can be described as a potentially entirely new way of imaging—called Quantum Ghost Imaging—through scattering and absorbing media; and promising work on social network analysis that focuses on constructing and analyzing social networks from sparsely tagged, unstructured data for tactical "data-to-decision" relationship discovery service;
- The development of single-trial-based, Army-relevant paradigms for brain-behavior analysis, including the demonstration that electroencephalogram (EEG) recordings of brain activity can be analyzed on a trial-by-trial basis, using independent component analysis (ICA) methods to reveal the neural basis of "Shoot/Don't shoot" behavior;
- Leadership in the work in quantum detectors and III-nitride materials for sources and detectors, in acoustic processing and electromagnetic field sensing, and in semiconductor power switching and conditioning devices;
- State-of-the-art work on the compressor-tip-injection stall control that couples experimental data and computational fluid mechanics and will enable the industrial design community to improve gas turbine fuel economy and reduce compressor stall; windage work in high-speed gear systems that promises to improve gearbox efficiency across a wide range of vehicles; and groundbreaking work on microautonomous systems;
- The clear evolution of armor in various ways over the years as the threats have also evolved: in particular, improvised explosive devices are creating new demands on armor. Advances in materials and computational tools have made possible new approaches to address passive armor protection. The armor work highlighted for the Board clearly showed the strong value to the Army of the ballistic protection technology and development capabilities of the Weapons and Materials Research Directorate (WMRD). The results and accomplishments that were shown were very impressive and clearly demonstrate ARL's preeminent position in the United States in armor development; and
- The WMRD-led science and technology (S&T) effort that resulted in the type classification of the M855A1 round, providing an example of how the S&T program has changed within the Army. The M855A1 solves a need for an improved 5.56 mm round that can deliver more consistent antipersonnel lethality in a variety of operational scenarios and that can also deliver adequate performance against light armor and be environmentally friendly (green). The WMRD effort focused on gaining a detailed understanding of the causes of the performance issues associated with the current M855 round from the integrated viewpoints of aeroballistic, terminal ballistic, and personnel incapacitation concerns. This improved understanding permitted a WMRD-led team to identify a new design concept that could provide improved performance and also be more environmentally friendly than the currently fielded M855 round is.

Many ARL challenges require cross-directorate collaboration. ARL should continue to address several specific areas that require collaboration across ARL directorates. These areas include robotics and autonomous systems, computation and modeling, network science, energy science, and materials by design.

ARL has been responding admirably to severe pressures to transition new technologies quickly to the field and to address those challenging requirements of emerging Army programs at the same time that it maintains its role with respect to longer-term basic research. The types of endeavor involved in responding quickly to immediate challenges are very important for ARL, but it must be emphasized that basic research is a foundation for future R&D accomplishments.

ARL has been successfully addressing these significant challenges by its careful management of technical resources. Through its extensive interactions with the external academic, industrial, and government R&D communities, ARL develops opportunities to hire talented scientists, engineers, technicians, and managers. Contacts are developed through the many collaborative activities in which staff participate, through the Army Research Office, and through regular stakeholder meetings, planned interaction with academic organizations, and regular recruiting activities. ARL's ability to secure needed talent would be enhanced by any administrative adjustments that improved speed and flexibility with respect to new appointments. Sufficient funding should be provided to ARL so that funding is not a constraint on managers' ability to enable the interactions of ARL staff with the scientific community through travel to professional meetings. ARL management should continue to encourage and support its staff to publish in scientific, peer-reviewed journals and proceedings.

The following discussion addresses each of the ARL directorates and includes crosscutting areas and significant advancements and opportunities.

## COMPUTATIONAL AND INFORMATION SCIENCES DIRECTORATE

Several technology issues have cut across multiple ARL directorates, but with particular impact on the Computational and Information Sciences Directorate (CISD). Examples include advanced computing, networking (especially ad hoc networking), information fusion, information security, system-of-systems analysis, prototyping, and validation and verification (V&V). ARL has initiated efforts that address many of the issues covered by this report, including advanced computing, information fusion, and networking. Other areas, such as information security, system-of-systems analysis, and V&V, could benefit from more crosscutting activities. In addition, however, there are several new areas that may also qualify for ARL-wide consideration:

- *Microrobotics:* The need for surveillance, especially at the squad level, has continued to expand, and the introduction of ever-smaller platforms is continuing to offer new opportunities for deployment. CISD is potentially at the heart of such systems, which involve networking, information fusion, high-performance onboard image processing, and the ability to carry weather detectors and/or be influenced by micro weather events. New capabilities such as swarming and electronic warfare (jamming) will also clearly involve not only CISD but will also interact with the Sensors and Electron Devices Directorate (SEDD) in the development of new sensors compatible with limited resources and the Vehicle Technology Directorate (VTD) when computing can simplify platforms.
- *Power:* Power or, more precisely, energy consumption, has become a first-class design constraint on almost all Army platforms, especially as more and more functionality is done with computing.
- *Prognostics and diagnostics:* This area involves platform-based fault detection and reconfiguration. The increase in platform complexity and the increasingly rapid schedule of introduction, deployment, and retirement mean that the average soldier who must deal with complex equipment barely has time to learn to use a new system, let alone to become expert enough to be able to repair or reconfigure it. Computing must take a central role in the automation of platform-based fault detection and reconfiguration, but it must do so in ways that are compatible with the platforms and that simplify the soldier's overall workload. CISD needs to be involved both in platform-based

fault detection and reconfiguration and in remote real-time data mining, parameter extraction, trend analysis, and real-time modeling.

- *Biomechanics:* CISD does not have a central role in the area of biomechanics at present. The topic falls within the scope of the Human Research and Engineering Directorate (HRED). However, there will be a need to develop and then support significant modeling activities using high-performance computing expertise, facilities, and resources.
- *Acoustics:* Already a strong area in CISD's research portfolio, acoustics will increase in importance as additional sensors and additional laboratories such as HRED's Environment for Auditory Research (EAR) come online and require modeling support, data visualization, and correlation with atmospheric effects.
- *Modeling and computational science:* This area clearly overlaps multiple components of CISD's charter and continues to be an identified area for crosscutting activities.

Identifying potentially disruptive technologies that might radically change the problems facing the Army is an issue of ARL-wide importance. The Army needs to leverage technology to respond to events like the rise of asymmetrical warfare and improvised explosive devices. In CISD's domain, as in the Army more broadly, change in technologies occurs exceedingly rapidly. Therefore, each of the CISD divisions, CISD as a whole, and ARL in general will benefit from the development of a formal mechanism to help identify critical technologies in a timely fashion.

## HUMAN RESEARCH AND ENGINEERING DIRECTORATE

The Human Research and Engineering Directorate has a vast and very important mandate: to understand the functions of the human-in-the-loop in a wide range of Army systems. The most sophisticated sensors, weapons, and information systems will not deliver their full potential if they are not well matched to the capabilities of the humans using them in the conditions under which they are intended to be used. This human-in-the-loop domain includes a wide range of research topics, from basic to applied. Perhaps the fundamental challenge for an organization like HRED is how best to select some subset of the vast number of possible topics for study.

HRED's ability to perform high-level, fundamental research has been enhanced by several factors:

1. The influx of talented, early-career new hires;
2. The use of Collaborative Technology Alliances; and
3. The development of significant new facilities, including the Cognitive Assessment, Simulation, and Engineering Laboratory (which is open); the Environment for Auditory Research (open); and the facility for Soldier Performance and Equipment Advanced Research (in development).

The Human–Robot Interaction Program has shown progress during the reporting period, particularly in the work incorporating real robots and addressing important field-motivated questions and in the increased consideration of scenarios involving soldiers controlling more than one robotic platform at a time. The group needs to continue its efforts to interact with the broader academic robotics community in order to stay abreast of cutting-edge methods. New resources and new hires may be required in order to make progress in some important areas (e.g., cognitive robotics). Connections with other Army robotics research should be facilitated. In particular, there should be opportunities for crosscutting interactions with SEDD and CISD.

The Human System Integration (HSI) Division continues to have a leadership role in the development of models, tools, and methods to support the assessment and evaluation of warfighter systems. IMPRINT—Improved Performance Research Integration Tool—the division's most significant tool, continues to improve with the development of new plug-ins and through collaborations with a range of users. The ARL Field Assistance in Science and Technology (FAST) presentation to the Board described applications of human factors engineering in Iraq, compellingly illustrating the value of the deployment of HRED personnel to theater where they can obtain a first-hand understanding of the problems faced by ARL end users (i.e., soldiers). Because of the high demand for specific Manpower and Personnel Integration services, the HSI Division faces a continuing challenge in the balancing of fundamental research and work for Department of Defense (DoD) consumers. The group could usefully absorb an influx of staff and financial support. This would expand the impact of its work within and beyond its immediate Army customers and would allow the group to publish more in Tier 1 peer-reviewed proceedings and journals.

The relatively new neuroscience group has been a model of early program development, with clearly defined goals and a membership including talented, early-career scientists. The group is poised to make significant basic and applied contributions in the young field of neuroergonomics. To date, most progress has been made in the area of EEG measures of soldier performance, including the effort to make EEG recording practical under field conditions. A new CTA promises to open up a broad area of research in the next few years. The primary challenge faced by the neuroscience group is that of managing growth, because it will need expanded staff and facilities in order to meet its potential. As it grows, the group may be able to exploit unique opportunities, presented by its Army setting, for research on multimodal integration, regulation of brain processes, and neuroplasticity.

The social and cognitive network science group works on a timely set of problems. An important challenge for the group, noted in the previous ARLTAB report[1] and still relevant, is to focus the group's energies on specific domains within a vast field. Some progress has been made, with an emphasis on improving distributed collaboration and decision making in warfighters' complex networked environments by using cognitive science, computer science, and social network innovations. New staff and funding have been obtained. Some projects have been completed (e.g., a study of the effects of network delays on communication outcomes and a qualitative linguistic study of misunderstandings that arise in communications among members of cross-cultural teams). However, the scientific output of program research, as reflected by publications in peer-reviewed journals, remains less than desired over time and in comparison with other programs within HRED. The social and cognitive network science group needs to develop a strategic plan directing the choice of research thrusts and projects that enable the program to contribute both to theory and to warfighter application in the social and cognitive network science domain. The group is in a unique position to study, for example, large-scale field exercises involving a significant number of participants over several days' time. Most critically, the group needs to develop a strategic plan directing the choice of research thrusts and projects that will enable the program to contribute to basic science and to warfighter applications.

The soldier performance group has overseen the development of two state-of-the-art facilities: the Tactical Environment Simulation Facility and the Environment for Auditory Research. An important challenge for the group is to realize the potential of these facilities for in-house research and joint research with collaborating researchers. The issue of a usage plan for the EAR was raised in the previous ARLTAB report and remains a challenge. The group conducts a wide range of specific research projects in the soldier performance area. Some, like the Auditory Hazard Assessment Algorithm for Humans,

[1]National Research Council. 2009. *2007-2008 Assessment of the Army Research Laboratory*. Washington, D.C.: The National Academies Press.

constitute significant contributions. In other areas (e.g., sensor fusion), contributions are less dramatic, and it appears that more contact could be made with researchers within and outside of DoD. In some cases (e.g., studies at Fort Sam Houston on post-traumatic stress disorder), decisions need to be made as to whether HRED should pursue the research topic, important as it is, or whether other DoD groups are better positioned to carry out such work.

## SENSORS AND ELECTRON DEVICES DIRECTORATE

The Sensors and Electron Devices Directorate is expected to update its research portfolio continuously in order to keep pace with changes in sensors and electronic device technology. SEDD has addressed this responsibility by increasing its in-house research efforts in several areas, such as wide bandgap materials, image processing, flexible displays, and battery chemistries, while moving on from unattended ground sensors and sensor integration, and transitioning silicon carbide device research from in-house to external projects. Significantly, these changes are guided by a clearly stated long-term vision for each of the major SEDD mission areas. For example, the extreme energy and power vision describes an objective of providing the individual soldier with access to two or three augmented energy sources on the mesoscale and microscale. The heterogeneous electronics vision foresees intelligent systems built from multiple technologies and integrated into clothing, vehicle surfaces, and other stuctures in the warfighter's environment.

SEDD facilities and equipment must evolve as its research portfolio evolves. Accordingly, SEDD has invested $12.5 million in new equipment and laboratories. Most of these funds were spent on new and upgraded instrumentation, and investments were spread across all of the SEDD divisions. Among the "crown jewels" of SEDD facilities is its extensive semiconductor fabrication facility. This facility has developed into an extraordinary research support tool capable of producing a diverse set of advanced semiconductor devices, all of which are critical to the SEDD mission. However, even though it has been continuously upgraded since 2002, the semiconductor fabrication facility is in need of a major review. Much of the processing and support equipment is nearing the end of its useful life span. The maintenance status and the impact of the introduction of new process procedures need to be reviewed. ARL and SEDD management needs an independent, objective look at all of these issues and must be prepared to make a significant investment in the near future to keep this capability at the cutting edge.

There are several other crown jewel projects in which SEDD researchers are leading the field. Most notable is the work in quantum detectors and III-nitride materials for sources and detectors. SEDD's leadership in this field stems not just from its top-notch scientific staff but also from the fabrication facilities—among the best in the world—that it maintains. Another area of SEDD leadership is in acoustic processing and electromagnetic field sensing. SEDD researchers in this area can point to immediate impacts on the battlefield; several systems from this group have been deployed in recent years. Semiconductor power switching and conditioning devices are also an area of leadership. This reflects a combination of quality staff, excellent facilities, and a direct application to Army requirements. Although its participation in the Flexible Display Center is not an internal program, it is important to note the role that SEDD plays in the center. The flexible display technology has potentially extensive consumer and military applications. However, in some specifications, devices for these two markets may not coincide. The participation of SEDD in this center, generally to assist in the advancement of the technology, but additionally to see that military needs are met, shows significant foresight by ARL and SEDD management.

## SURVIVABILITY AND LETHALITY ANALYSIS DIRECTORATE

The Survivability and Lethality Analysis Directorate (SLAD) provides sound assessment and evaluation support with respect to the survivability, lethality, and vulnerability of Army equipment and soldier systems to ensure that soldiers and systems can survive and function reliably in the full spectrum of battlefield environments. SLAD is well staffed with bright, creative professionals enthusiastic about their mission, and its facilities include state-of-the-art laboratories. SLAD has many opportunities to expand its testing and evaluation base through select program expansion aimed at developing tools and methodologies to broaden the directorate's analysis capabilities and at defining and maintaining the competitive edge required to be the Army's primary source for survivability, lethality, and vulnerability assessment. The system-of-systems analysis program and the Modular UNIX-based Vulnerability Estimation Suite, or MUVES 3, program continue to cause significant concern, but with appropriate focus these programs can grow to become foundations of the SLAD analysis capabilities.

In wartime, rapid response to soldier-in-the-field challenges is imperative. SLAD personnel have provided exemplary service to their country in this time of war, with their dedication and "can-do" attitude. This highly motivated, mission-aligned, enthusiastic group of engineers and technicians has made significant contributions to the Army and DoD through creative problem solving and solid engineering know-how. An excellent example of this effectiveness is the program in radio-frequency countermeasures. This program is very impressive. This group has provided effective response to Army needs and support of Army personnel, demonstrating a high-energy, creative approach to solving problems quickly while maintaining cost-consciousness. This support work for the Joint Improvised Explosive Device Defeat Organization is commendable and an impressive help to Army field personnel. The modular approach used in this program ensures extensibility of the methodology to enable quick turnaround on future problems. This program also shows a good use of existing software for analysis.

The Target Interaction Lethality/Vulnerability (TILV) Program is an excellent example of an SLAD strategic program aimed at improving SLAD's vulnerability analysis capabilities. A typical TILV project is 3 to 4 years in duration and is designed to address a significant methodology shortfall. Some of examples of recent TILV projects include studies of underbody blast effects and ballistic helmet impacts.

The development of underbody blast methodology is well thought out and is commendable for filling a critical need in this area. The methodology combines appropriate physics and necessary codes to assess damage to vehicles. There is a good understanding of the limitations of the various elements that are interconnected to form the overall methodology. This is a notable example of research that could have an impact on the next generation of vehicles. The work is being presented at appropriate conferences and would benefit from peer review for publication in archival journals.

The study of ballistic impacts on helmets is a good example of solid engineering using well-established principles to improve test standards. This program provides an excellent opportunity to collaborate with outside experts to define and conduct further research efforts in this area.

In contrast with the program portfolios of many of the other ARL directorates, the SLAD program portfolio includes relatively few applied research programs and no basic research program. The vast majority of SLAD programs are funded at much later stages in the DoD research, development, testing, and evaluation chain supporting acquisition and deployment programs. The SLAD portfolio and evaluation structure are based strongly in its long history of ballistics-based vulnerability assessment. It is commendable that SLAD has broadened its program base to include the assessment of communication, network, and information-processing vulnerability on the battlefield; nonetheless, the efficacy of the SLAD tool development methodology may not be sufficient to identify and stay ahead of the rapidly emerging threats to network-centric warfare in an irregular battlefield environment.

SLAD's implementation of a matrix structure seems a creative way to balance the culture of innovation and prototype development with program support. This approach should be promoted. A critical concern, however, is whether the leaders who are equivalent to program and/or project managers have the requisite control over resources necessary to be responsive to sponsors' needs, or whether they are simply internal coordinators.

SLAD management is aware of the importance of hiring creative, energetic, and innovative professionals, as well as competent and enthusiastic early-career engineers and interns. Management also recognizes the value of professional development and provides several methods for this: pursuit of advanced degrees, certifications, personal leadership opportunities, developmental assignments, conferences, and collaborations. More emphasis should be placed on continued education, both to enhance the knowledge and experience base in the principles of basic research and to broaden the scope of collaboration outside ARL.

## VEHICLE TECHNOLOGY DIRECTORATE

The Vehicle Technology Directorate has established the tradition of a research approach that successfully applies analytical tools and experimental techniques in a controlled environment to hardware-based problems of various scales. In many areas, VTD research is contributing to both fundamental and applied levels of technology. In addition, many examples exist of the work of VTD fulfilling both current and future Army needs. VTD has been continually demonstrating evidence of the increasingly high quality of its research. The 2005 Base Realignment and Closure (BRAC) decision requiring consolidation of VTD at Aberdeen Proving Ground, Maryland, coupled with VTD management's evolving focus on Army needs, is increasing the quality of the VTD research portfolio.

The establishment of eight capability concepts that embody clearly defined future Army needs is a good example of VTD focus as it moves from research emphasis on helicopter-type vehicles to research emphasis on smaller, autonomous robotic vehicles. The capability concepts approach also improves the quality of the research portfolio by allowing VTD management to ensure that all of the research needed to support each capability concept is underway by the technical community either inside or outside VTD. The recognition that a crawling-bug-type vehicle needs to be added to the Micro Autonomous Vehicle Capability Concept is a clear example of management's understanding of the Army's need in this research area. In a similar manner, the capability concepts approach allows VTD to prioritize research so that research impacting several capability concepts can be moved forward, or research that does not apply to any capability concept might be redirected or stopped. The combustion of Jet Propellant 8 (JP-8) fuel in a very small volume is an example of a crosscutting technology area that would impact several capability concepts, and it is therefore a high-priority research area.

Some of VTD's high-quality technical work is clearly an important contribution to the overall technical community. For example, the compressor-tip-injection stall control work that couples experiment data and computational fluid mechanics is state of the art and will enable the industrial design community to improve gas turbine fuel economy and reduce compressor stall. In a similar manner, the windage work in high-speed gear systems is state of the art and promises to improve gearbox efficiency across a wide range of vehicles. The research in microautonomous systems is groundbreaking work. The researchers involved in this work are of high quality. The development of a complete portfolio of work in this area and the addition of new team members will improve the focus of this work.

There are emergent areas and opportunities in engineering in mesoscale and bio-inspired systems. These scales represent an opportunity for VTD to take a leadership role. Moreover, this scale of system is likely to be compatible with a multitude of systems for the soldier—for example, squad- or platoon-level reconnaissance assets utilizing new concepts for air and ground vehicles.

There is a need for the modeling of vehicle systems in VTD. The results of good models, such as performance prediction and scalability studies, seemed absent in many of the VTD project descriptions provided to the ARLTAB. Robotic platforms and air vehicles need modeling to enable understanding of performance limits and optimization of platform parameters. Modeling is also critical to system design; good models are the key to insight into the underlying physics, from which meaningful functional and performance metrics can be developed and understood.

VTD should consider undertaking an effort in each of the following emerging technology areas: mesoscale power sources, such as small fuel cells and gas turbines; the analytical modeling of physical processes such as combustion; and simulators for the training of operators of remotely piloted air and ground vehicles.

High energy density power systems will be a disruptive technology in future Army vehicles. Therefore, VTD should develop and sustain its capability to take a leadership role in some classes of the DoD small engine initiatives. The Vehicle Applied Research Division will be of great help in determining in which classes VTD should have the natural leadership role. That is, in order to decide where natural leadership roles exist, VTD should carefully define classes of small engines. For example, a characterization of classes might be as follows: (1) gas turbines: from 3,000 to 10,000 shaft horsepower (hp); (2) internal combustion engines: from 2 to 50 hp; (3) electrical engines: from 0.1 to 10 hp; and (4) hybrid power systems. For example, one area of research that deserves consideration is power sources for baseball-size vehicles. The energy per unit of mass achievable from common hydrocarbon fuel is more than an order of magnitude greater than what can be achieved with batteries. Thus, an attempt to develop efficient and stable combustors of smaller volume (a cubic centimeter to a few cubic centimeters) for these baseball-size vehicles could produce significant payoffs for small autonomous air and ground vehicles. The number of engine classes needed by the Army and the enabling technology required will exceed the resources of VTD. However, careful selection of primary leadership classes and classes in which VTD needs to leverage the work of other government agencies and industry is the information needed to make the Army an intelligent buyer and will be of great use in focusing VTD.

The materials science and technology area is of particular importance to VTD. Addressing the need to develop this area requires that personnel embedded in VTD collaborate with others at ARL, universities, and other laboratories. The new VTD laboratory facility and the embedded capabilities of the Weapons and Materials Research Directorate can be utilized to attract new researchers, faculty, and students for summer internship programs and develop existing personnel in this vital area.

## WEAPONS AND MATERIALS RESEARCH DIRECTORATE

The Weapons and Materials Research Directorate continues to conduct science and technology of very wide breadth and great depth for purposes that include the protection of warfighters and their being provided with robust lethal instruments to carry out their mission objectives.

High-quality research is underway in almost all WMRD areas of interest: materials development and characterization thrusts, model development, and simulation. The WMRD-led S&T effort on the M855A1 round and the affordable precision munitions program are examples of the strong technical expertise embodied within ARL. ARL is strongly encouraged to continue its focus on capturing and controlling the intellectual property and modeling and simulation expertise in the protection and lethality areas.

The experimental results and simulations used to analyze the path of projectiles stabilized by gyroscopic control are very impressive. The analysis being conducted is well conceived and provides clear evidence for the value of the proposed control mechanism (taking advantage of a control spinner from the rear). This project represents success for WMRD on several fronts: WMRD designed a reduced system of ordinary differential equations that is capable of reproducing the controlled trajectories well and hence may lend itself better to onboard calculation; the design that followed provided the use of a spinner to stabilize and control projectile trajectories. WMRD provided a clear analysis (by customer request) of the flight dynamics of a retrofitted projectile and an explanation of why it does not lend itself to adequate control. WMRD's experimental and modeling efforts in this area represent the state of the art within DoD.

As the path to the development of advanced modeling and simulation tools aimed at predictive capability to support future systems, WMRD is strongly encouraged to continually refine models coupled to systematic validation experiments over a range of scales and to be mindful of quantitative assessment of the margins and uncertainties in their numerics and simulations.

WMRD is pursuing a mission that is well suited to its excellence in S&T in the areas of protection and lethality and is serving the short-term tactical needs of the warfighter as well as following an S&T vision to prepare for wars of the future. That said, there remain opportunities and challenges. WMRD has continued to increase its emphasis on coupling experimental and modeling efforts within its programmatic efforts; achieving and maintaining this balance constitute a worthy goal. Neverthless, error convergence in all modeling and simulation efforts should still be pursued and can be improved. In addition, verification and validation, while more obvious in the current review cycle than ever before, should continue to receive attention. More case studies in which the accuracy of the codes is checked against validation experiments should also be strongly encouraged by WMRD management.

The reinvigorating effects of new early-career staff were very evident during the current review cycle. This hiring trend should be continued as the path to sustainable excellence in the areas of protection and lethality.

WMRD is making an investment in energetics synthesis as a national asset to support both Department of Defense and Department of Energy programs. WMRD and ARL deserve commendation for initiating this effort and should continue to pursue building a core program in this area.

Much of WMRD's program in energetics materials modeling appears to emphasize quantum chemical modeling heavily, and experimental investigation and verification appear to receive less emphasis. The energetics materials modeling effort should be focused on a few challenging problems selected from appropriate length scales.

WMRD's control of the intellectual property in the area of precision design projects is an excellent approach to the development of new munitions because it helps to maintain expertise within DoD through such means as patents and publication. Holding the intellectual property within the Army and within DoD should be encouraged across an increasing number of technical S&T areas. The low-cost precision munition is a strong success story, of which the Excalibur project is an example.

The WMRD program in advanced weapons concepts is designed to identify projects that have high risk and high payoff for the Army. Innovative ideas are sought from WMRD researchers and leadership that bear on the mission of the Lethality Division and meet immediate or perceived future needs of the Army. The number of in-house proposals considered has grown from 4 in fiscal year (FY) 2009, to 11 in FY 2010, to 31 for FY 2011, demonstrating the success in stimulating idea generation within the division. Interaction with the warfighter has occurred in evaluating the utility of some proposals. Input has also been sought from the U.S. Army Training and Doctrine Command and other Army customers.

Based on the success of this program in advanced weapons concepts in the Lethality Division, it appears that similar programs should be launched in other areas within WMRD's portfolio. This program should be continued as long as funding criteria are such that high-risk, high-payoff projects are likely to be funded over those that are deemed to be more conventional and that program funding is not used to augment or supplant standard funding mechanisms. Researchers in the Lethality Division should be encouraged to identify customer proponents to enhance the likelihood that standard project funding will follow closely after the success of the initial project.

# 1

# Introduction

This introductory chapter describes the biennial assessment process conducted by the National Research Council's (NRC's) Army Research Laboratory Technical Assessment Board (ARLTAB). It then describes the preparation and organization of the report, the assessment criteria, and the approach taken during the report preparation.

## THE BIENNIAL ASSESSMENT PROCESS

The charge of ARLTAB is to provide biennial assessments of the scientific and technical quality of the Army Research Laboratory (ARL). These assessments include the development of findings and recommendations related to the quality of ARL's research, development, and analysis programs. The Board is charged to review the work of ARL's six directorates but not to review two key elements of the ARL organization that manage and support basic research: the Army Research Office (ARO) and the Collaborative Technology Alliances (CTAs). Although the primary role of the Board is to provide peer assessment, it may also offer advice on related matters when requested to do so by the ARL Director; such advice focuses on technical rather than programmatic considerations. The Board is assisted by six NRC panels that focus on particular portions of the ARL program. The Board's assessments are commissioned by ARL itself rather than by one of its parent organizations.

For this assessment, ARLTAB consisted of seven leading scientists and engineers whose experience collectively spans the major topics within the scope of ARL. Six panels, one for each of ARL's directorates,[1] report to the Board. Six of the Board members serve as panel chairs. The panels range in

[1]The six ARL directorates are the Computational and Information Sciences Directorate (CISD), Human Research and Engineering Directorate (HRED), Sensors and Electron Devices Directorate (SEDD), Survivability and Lethality Analysis Directorate (SLAD), Vehicle Technology Directorate (VTD), and Weapons and Materials Research Directorate (WMRD). The Board

size from 10 to 20 members, whose expertise is carefully matched to the technical fields covered by the directorate(s) that they review. In total, 96 experts participated, without compensation, in the process that led to this report.

The Board and panels are appointed by the National Research Council with an eye to assembling balanced slates of experts without conflicts of interest and with balanced perspectives. The 96 experts include current and former executives and research staff from industrial research and development (R&D) laboratories, leading academic researchers, and staff from Department of Energy national laboratories and federally funded R&D centers. Twenty-eight of them are members of the National Academy of Engineering, 4 are members of the National Academy of Sciences, and 1 is a member of the Institute of Medicine. A number have been leaders in relevant professional societies, and several are past members of organizations such as the Army Science Board and the Defense Science Board. The Board and its panels are supported by NRC staff, who interact with ARL on a continuing basis to ensure that the Board and panels receive the information that they need to carry out their assessments. Board and panel members serve for finite terms, generally 4 to 6 years, staggered so that there is regular turnover and a refreshing of viewpoints.

Biographical information on the Board members appears in Appendix B, along with a list of the members of each panel.

## PREPARATION AND ORGANIZATION OF THIS REPORT

The current report is the sixth biennial report of ARLTAB. Its first biennial report was issued in 2000; annual reviews by the Board had been issued in 1996, 1997, and 1998. As with the earlier reviews, this report contains the Board's judgments about the quality of ARL's work (Chapters 2 through 7 focus on the individual directorates, and Chapter 8 provides a crosscutting overview of ARL). The rest of this chapter explains the rich set of interactions that support those judgments.

The amount of information that is funneled to the Board, including the consensus evaluations of the recognized experts who make up the Board's panels, provides a solid foundation for a thorough peer review. This review is based on a large amount of information received from ARL and on panel interactions with ARL staff. Most of the information exchange occurs during the annual meetings convened by the respective panels at the appropriate ARL sites. Both at scheduled meetings and in less formal interactions, ARL evinces a very healthy level of information exchange and acceptance of external comments. The assessment panels engaged in many constructive interactions with ARL staff during their annual site visits in 2009 and 2010. The dates of the panel site visits are included in the introductory section of Chapters 2 through 7 on the individual directorates. In addition, useful collegial exchanges took place between panel members and individual ARL investigators outside of scheduled meetings as ARL staff members sought additional clarification about panel comments or questions and drew on panel members' contacts and sources of information.

Each panel meeting lasted 2½ days, during which time the panel members received a combination of overview briefings by ARL management and technical briefings by ARL staff. Prior to the meetings, panels received extensive materials for review, including selected staff publications.

The overview briefings brought the panels up to date on ARL's long-range planning. This context-building step is needed because the panels are purposely composed mostly of people who—while experts

does not have a panel specifically devoted to the Army Research Office, which is another unit of ARL, but all Board panels examine how well the in-house research and development of ARO and ARL are coordinated. Appendix A provides information summarizing the organization and resources of ARL and its directorates.

in the technical fields covered by the directorates(s) that they review—are not engaged in work focused on Army matters. Technical briefings for the panels focused on the R&D goals, strategies, methodologies, and results of selected projects at the laboratory. Briefings were targeted toward coverage of a representative sample of each directorate's work over the 2-year assessment cycle. Briefings included poster sessions that allowed direct interaction of the panelists with staff of other projects that either were not covered in the briefings or had been covered in prior years.

Ample time during both overview and technical briefings was devoted to discussion, both to clarify the relevant panel's understanding and to convey the immediate observations and understandings of individual panel members to ARL's scientists and engineers. The panels also devoted sufficient time to closed-session deliberations, during which they developed consensus findings and identified important questions or gaps in panel understanding. Those questions or gaps were discussed during follow-up sessions with ARL staff so that the panel was confident of the accuracy and completeness of its assessments. Panel members continued to refine their findings, conclusions, and recommendations during written exchanges and teleconferences among themselves after the meetings.

In addition to the insights that they gained from the panel meetings, Board members received exposure to ARL and its staff at Board meetings each winter. The 2010 Board meeting focused on the assessment process, and discussions with the ARL management team led to improvements in the assessment process in terms of the panels receiving timely read-ahead materials for their meetings, the development of the panel meeting agendas, and more attentiveness to the assessment process time lines. Also, some Board members attended the annual ARL Program Formulation Workshop in 2009 and 2010; at these workshops the ARL directorates discussed their programs with the directorates' customers and stakeholders.

## ASSESSMENT CRITERIA

During the assessment, the Board and its panels considered the following questions posed by the ARL Director:

1. Is the scientific quality of the research of comparable technical quality to that executed in leading federal, university, and/or industrial laboratories both nationally and internationally?
2. Does the research program reflect a broad understanding of the underlying science and research conducted elsewhere?
3. Does the research employ the appropriate laboratory equipment and/or numerical models?
4. Are the qualifications of the research team compatible with the research challenge?
5. Are the facilities and laboratory equipment state of the art?
6. Does the research reflect an understanding of the Army's requirement for the research or the analysis?
7. Are programs crafted to employ the appropriate mix of theory, computation, and experimentation?
8. Is the work sufficiently unique and appropriate to the ARL niche?
9. Are there especially promising projects that, with application of adequate resources, could produce outstanding results that could be transitioned ultimately to the field?

Within the general framework described above, the Board also developed and the panels applied detailed assessment criteria organized in the following six categories (Appendix C presents the complete set of assessment criteria):

1. *Effectiveness of interaction with the scientific and technical community*—criteria in this category relate to cognizance of and contributions to the scientific and technical community whose activities are relevant to the work performed at ARL;
2. *Impact on customers*—criteria in this category relate to cognizance of and contributions in response to the needs of the Army customers who fund and benefit from ARL R&D;
3. *Formulation of projects' goals and plans*—criteria in this category relate to the extent to which projects address ARL strategic goals and are planned effectively to achieve stated objectives;
4. *R&D methodology*—criteria in this category address the appropriateness of the hypotheses that drive the research, of the tools and methods applied to the collection and analysis of data, and of the judgments about future directions of the research;
5. *Capabilities and resources*—criteria in this category relate to whether current and projected equipment, facilities, and human resources are appropriate to achieve success of the projects; and
6. *Responsiveness to the Board's recommendations*—with respect to this criterion, the Board does not consider itself to be an oversight committee. The Board has consistently found ARL to be extremely responsive to its advice, so the criterion of responsiveness encourages discussion of the variables and contextual factors that affect ARL's implementation of responses to recommendations rather than an accounting of responses to the Board's recommendations.

## APPROACH TAKEN DURING THE REPORT PREPARATION

This report represents the Board's consensus findings and recommendations, developed through deliberations that included consideration of the notes prepared by the panel members summarizing their assessments. The Board's aim with this report is to provide guidance to the ARL Director that will help ARL sustain its process of continuous improvement. To that end, the Board examined its extensive and detailed notes from the many Board, panel, and individual interactions with ARL over the 2009-2010 period. From those notes it distilled a shorter list of the main trends, opportunities, and challenges that merit attention at the level of the ARL Director. The Board used that list as the basis for this report. Specific ARL projects are used to illustrate these points in the following chapters when it is helpful to do so, but the Board did not aim to present the Director with a detailed account of 2 years' worth of interactions with bench scientists. The draft of this report was subsequently honed and reviewed according to NRC procedures before being released.

The approach to the assessment by the Board and its panels relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the technical areas within which the ARL activities are conducted. The Board and its panels reviewed selected examples of the standards and measurements activities and the technological research presented by ARL; it was not possible to review all ARL programs and projects exhaustively. The Board's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the technical merit of the ARL work, its perceived relevance to ARL's definition of its mission, and apparent specific elements of ARL's resource infrastructure that is intended to support the technical work. Collectively, these highlighted examples for each ARL directorate are intended to portray an overall impression of the laboratory while preserving useful mention of suggestions specific to projects and programs that the Board considered to be of special note within the set of those examined. The Board applied a largely qualitative rather than quantitative approach to the assessment; it is possible that future assessments will be informed by further consideration of various analytical methods that can be applied. The assessment panels' site visits are currently scheduled to be repeated annually and the assessment report to be issued biennially.

## REPORT CONTENT

This chapter discusses the biennial assessment process used by ARLTAB and its six panels. Chapters 2 through 7 provide a detailed assessment of each of the six ARL directorates. Chapter 8 presents an overview focused on crosscutting issues across all of ARL. The appendixes provide the ARL organizational chart and staffing profile, biographical information on the members of ARLTAB and a list of the membership of its panels, the assessment criteria used by ARLTAB and its panels, and a list of acronyms found in the report.

# 2

# Computational and Information Sciences Directorate

## INTRODUCTION

The Computational and Information Sciences Directorate (CISD) was reviewed as a whole by the Panel on Digitization and Communications Science during the periods July 7-9, 2009, and July 6-8, 2010. The reviews consisted of overviews given by management of the directorate and its divisions, presentations on a subset of current projects, poster sessions at which project leaders were available, and laboratory tours.

CISD has stabilized its organization at the same four research divisions discussed in the previous report of the Army Research Laboratory Technical Assessment Board (ARLTAB)[1]: the Advanced Computing and Computational Sciences Division (AC&CSD), Battlefield Environment Division (BED), Information Sciences Division (ISD), and Network Sciences Division (NSD). CISD is responsible for Collaborative Technology Alliances (CTAs) on Communications and Networking (this CTA ended in FY 2009) and on Networks (started in FY 2010), a continuing International Technology Alliance (ITA) on Network and Information Sciences, and a Mobile Network Modeling Institute. CISD is also responsible for the Army High Performance Computing Research Center at Stanford University.

CISD's expressed mission is unchanged from that cited in the previous ARLTAB report: to create, exploit, and harvest innovative technologies to enable knowledge superiority for the warfighter through advanced computing, network and communication sciences, information assurance, and battlespace environments. To carry out this mission, CISD performs research for the following purposes:

[1]National Research Council. 2009. *2007-2008 Assessment of the Army Research Laboratory*. Washington, D.C.: The National Academies Press.

- To advance computational sciences and high-performance computing (HPC) technologies in support of Army systems;
- To enhance warfighter effectiveness through environmental knowledge and technology;
- To provide fused, timely information from all relevant sources to the warfighter; and
- To develop self-configuring wireless network technologies that enable secure, scalable, energy-efficient, and survivable tactical networks.

ARLTAB's previous report highlighted continuing significant advances made by CISD in the machine translation (MT) of foreign languages, atmospheric acoustics and radio-frequency (RF) and optical propagation in battlefield environments, and surface-level weather modeling. Promising advances were reported in experimental sensor systems (chemical and particle detection in aerosols and the atmosphere, microfluidic devices, and quantum dot formation for night-vision goggles); in the transition of previous prototype systems to products (e.g., achieving a 100-times reduction in the weight of a compact lidar system); in the development of a small, standardized battlefield network interface called the Blue Radio; and in theory and modeling (improving models of turbulence in the atmosphere, codes to design application-specific microfluidic devices, and calculations of binding affinities for potentially toxic chemical and biological compounds). All of these advances had two common characteristics: solid science and a clear understanding of the relationship to real Army problems.

Areas that were deemed challenges in the previous ARLTAB report included a need for more of a systems engineering outlook in projects, validation and verification (V&V) of models and computer codes, an increasing need to perform sophisticated analyses and data mining on experimental data, and the need to find a way to leverage the work done to date on Blue Radio (especially how to achieve a single-chip implementation that could be used in a variety of systems). The challenge of expanding beyond traditional computing applications could benefit, as indicated in the previous report, from the development of an ability to accumulate, analyze, understand, and efficiently process human and electronic intelligence about relationships between individuals and organizations in an asymmetric battlespace. Challenges also existed in moving the weather-modeling efforts from a concentration on the modeling of atmospheric physics to the building of real applications on top of such models. In the high-performance computing area, a need for additional research and development (R&D) resources was identified, specifically for developing a professional staff that is capable of building HPC software products that are efficient and application-specific. There also appeared to be a lack of HPC vision in the non-AC&CSD divisions of CISD.

Table A.1 in Appendix A characterizes the staffing profile for CISD.

## CHANGES SINCE THE PREVIOUS REVIEW

Since the site visit of the panel in 2009, there has been no change in the overall organization of CISD and only one management change at the level of division chief. This degree of stability is in positive sharp contrast to the situation in prior years.

In terms of Collaborative Technology Alliances, both the Communications and Networking CTA and the Advanced Decision Architectures CTA (which CISD partnered with the Human Research and Engineering Directorate [HRED]) were completed, and work continued on the International Technology Alliance on Network and Information Sciences, initiated in 2008. The focus of this ITA is on managing end-to-end information flows in support of coalition decision making. The Networks CTA was started in FY 2010.

## ACCOMPLISHMENTS AND ADVANCEMENTS

### Document Management for Foreign-Language Machine Translation

CISD continues to demonstrate extraordinary advances in deployable facilities for the machine translation of foreign-language material in ways that are clearly relevant to real Army problems. The focus of prior related research has been first on speech translation and then on text translation, with an emphasis on the rigorous evaluation of alternative algorithms and on combining them to improve translation performance. In this reporting period, CISD reported a program of research that did not address machine translation itself, nor the merits of various algorithms and software; instead, it addressed putting machine translation into a key downrange application. Given that the Army is composed almost entirely of people whose native language is English and that most of its overseas deployments are in non-English-speaking parts of the world, developing tools to help English-speaking soldiers leverage MT technology is a very worthy research direction for ARL. In particular, the research reviewed in this period focused on creating and optimizing work flows for leveraging existing MT technology to address the automated analysis of large volumes of foreign-language paper documents. The objective is a cradle-to-grave process that starts with scanning and optical character recognition (OCR), continues through machine translation, and ends with the categorization, analysis, and storage (in a searchable and retrievable fashion) of the content—in English. The selected work flow is adaptive, and it can be arranged to process documents automatically or semiautomatically (with human annotations), or customized to use low-level domain information. Particularly impressive is that readers who do not read Arabic and are not linguists could be part of the flow for unclassifiable documents, recognizing the structure of a document from nontextual clues (format, letterheads, pictures) and inputting this information to aid the MT process.

The evaluation process for this work continued the solid approaches employed in earlier years and was done by using the Anfal corpus, produced after the First Gulf War, which is very large and contains many different forms of documentation and correspondence. Particularly notable was the use of well-conceived statistical techniques to bin the samples and organize the work. Similar work addressed the translation of domain-specific texts from English to Dari, something that is of real value in the Afghanistan theater.

This work also is a powerful example of the great potential for exploiting synergies across multiple projects toward sustainable innovations that could move forward the data-to-decision mission of CISD in general. In particular, with a focus on interoperable data acquisition, processing, and metadata services, there is the potential to develop rich data collections that could not be developed otherwise. Additionally, methods for data exploitation share many common algorithms related to clustering, classification, and network analysis that could benefit from shared approaches to scaling to bigger data sets through performance modeling and parallel computing. New optimization methods or rule-based systems could also be developed for translating these algorithmic outputs to new, Army-relevant decision-support measures and metrics that can be adapted and tuned through experiment and feedback from end users. It is therefore important to provide the needed resources and support for a systematic specification and development process with a data sets approach to code reuse and interoperability in order to enable the development of new sustainable pathways for growing this emerging area.

### Quantum Ghost Imaging

Developing imaging sensors for bad weather environments has long been an Army Research Laboratory (ARL) strength, bolstered by world-class work on infrared (IR) sensors at the Sensors and Electron

Devices Directorate (SEDD). In this reporting period, however, new work has combined ARL's strengths in quantum physics with advanced high-performance computing to perform first-in-the-world demonstrations for what can be described as a potentially entirely new way of imaging through scattering and absorbing media. Light from a scene is split into a conventional charge-coupled device camera and a single-pixel sensor, with a point-to-point 2-photon Glauber coherence correlation, to form an image. Performing this correlation is a very heavily computationally-intensive problem.

The significance of the work was clear both from the demonstrations provided for the panel and from external validation through both multiple patents and multiple publications in very-high-impact publications with rigorous peer review. This is outstanding work in all respects—based on truly fundamental and novel physical design—and it is likely to lead to high-impact relevance for Army (and other) applications. It is an excellent example of a project based on fundamental physical drivers and real Army applications.

It is clear that there are multiple paths to both deploying and enhancing the technology and that such work is deserving of continued ARL support. Collaborations with HPC expertise should lead to the ability to perform the computations in closer to real time in a sensor platform compatible with battlefield conditions or conditions familiar to civilian first-responders (firefighters). Additional computation and/or sensing may also lead to ranging determination and/or increased resolution.

### Social Network Construction from Unstructured Input, Information Fusion, and Analysis

Over the past few years, the panel has encouraged CISD to explore computational tools to aid in performing social network analysis (SNA) based on intelligence and other data sources; in this sense a "social network" represents the relationships between humans. In the Army context, the most obvious but not the only example is the identification of the combatants engaged across the improvised explosive devices (IEDs) chain and the mapping of their functions, from the financiers, through the bomb makers and parts suppliers, to the IED placement and detonation teams. Results in Iraq using anthropologists, intelligence personnel, and relatively ad hoc tools have proven the potential value in trying to automate even further the construction of such human networks from disparate data sources.

CISD had acted on a previous panel's suggestion, hiring a social scientist to collaborate with a group of CISD computer scientists. Commendably, that social scientist is actually leading CISD colleagues in automating the fusion of data sources and the generation of the metadata tags on such data, which then allow for the kind of graph analysis that can reveal adversary networks. The discussion above on machine translation and analysis of documents provides an example of such data sources.

The SNA thrust being performed focuses on constructing and analyzing social networks from sparsely tagged, unstructured data for tactical data-to-decision relationship discovery service. The work is still early in its execution, but the hiring of new Ph.D.'s and the funding of Small Business Innovation Research (SBIR) projects indicate a seriousness that should have positive long-term consequences. The approach includes acquiring Army-relevant soft and hard data, then processing the data to derive metadata, followed by analysis on the SNA structure to reveal microscale relations and by analysis on the dynamics of network change with respect to macroscale events or processes that evolve on network structures over time.

The SNA team also appears to understand and articulate the key challenges in the task of integrating soft and hard data; the team was open to exploring the potential of new data-collection modalities that may help remove some of the underlying dichotomies, while at the same time working with another team on the integration issues. Of particular note is the deliberate choice to do early experiments on terabyte data sets in order to assess the challenging aspects of the problem in scales much larger than those of toy data sets in ways that are critical for meeting the discovery needs and testing of new analysis algorithms. The clear articulation of project goals and plans and the project's relevance to the Army mission were impressive. Additional strengths concerned the support of three new SBIR projects on source selection with strong potential for near-term successes; a focus on interdisciplinary collaboration; expanded interactions with the Office of the Secretary of Defense, the Multidisciplinary University Research Initiative, CTA, and end users; and initial experiments with Twitter feeds aiming at the development of a system that can incorporate streaming data.

Related work that also showed good experimental design and potential high relevance to Army needs was a study of how better visualization techniques (i.e., how to cluster for display purposes large amounts of disparate data) aid in reducing the timing of decision making in high-tempo workloads. The experiments were conducted with Reserve Officers' Training Corps (ROTC) students as subjects, with Army-relevant challenges. Collaboration with both academic institutions and HRED was excellent, with a strong transition plan to two Army Technology Objectives (ATOs): Advanced All-Source Fusion (A2SF) and Tactical Human Integration of Networked Knowledge (THINK).

Further work in several other areas might improve even more the future value of the overall SNA work, including the role of statistical analysis to quantify uncertainty, a more formal look at the algorithmic aspects of the underlying SNA schemes, and the role of different disciplines, including physics, biology, and computer science, in developing a team with the right set of skills and expertise. Plans for effective development and deployment of the relationship discovery service could benefit from bringing underlying systems and software engineering challenges to the forefront. The interdisciplinary team approach to meeting project requirements is commendable; CISD should consider identifying an additional systems leader—for example, one trained in computer science research with some explicit cross-training in the appropriate social sciences.

## High-Performance Computing

While managing some world-class computing facilities, the Advanced Computing and Computational Sciences Division has perhaps the least resources for research in all of CISD, in terms of both dollars and Ph.D.-level researchers. Given this limitation, in its previous report ARLTAB recommended that such resources as were available be focused on encouraging and developing an HPC capability in a much broader fashion than currently exists throughout ARL, and on developing software that ARL can take advantage of in future petaflops systems. In this 2009-2010 period, AC&CSD has made some significant strides in doing so.

In terms of producing HPC applications, the division has focused on developing a research portfolio that emphasizes applications that clearly cross divisional boundaries, such as support for lightweight combat systems and computational nanoscience and biological science. Although some of the work still suffers from a lack of focus on V&V of both the code and the underlying models, other work—such as modeling materials with complex microstructures that are hit with a shock of some kind, and the modeling of antimicrobial peptides with bacteria membranes—seems to be making real strides, particularly since the researchers focused on a good formulation of the problem with a solid initial approach, developed helpful collaborations with leading academic centers, and for at least early work included sound checks on the potential limits of the models (e.g., validity of a model when applied to more complex environments or processes). CISD should consider how to integrate such applications with other tools in a productive fashion, and it should also consider how to ensure a deployment path so that, if the effort is successful, the resulting code is not dropped, as was done with a prior Object Oriented MicroMagnetic Framework package.

In terms of addressing the rise of petascale computing, new efforts are underway to begin considering nontraditional HPC, namely, the potential in the near future of moving today's petascale supercomputing systems down into forms relevant to tactical environments, such as the back of a Humvee. Included are efforts to investigate new hardware technologies such as field-programmable gate arrays (FPGAs) and graphics processing units for computing-intensive applications such as tactical radars (synthetic aperture radars for detecting IEDs), battlefield weather prediction, RF propagation models, and mission planning, and also to investigate these technologies on domain-specific programming environments and compilers that might leverage such hardware in a more productive fashion than could be done using traditional tools. Neither these platforms nor the applications are traditional HPC targets, so it is not unexpected that there is a learning curve, with some false starts. However, the directions taken by CISD are very reasonable ones that should over the long term result in real new capabilities.

### Battlefield Weather

The efforts of the Battlefield Environment Division are clearly focused squarely on the key problems identified in the white paper entitled *Army Weather Support from the Army Intelligence Center,* with continued high levels of demonstrated expertise in virtually all areas that the division has addressed.

In what might be called traditional weather prediction, BED has provided repeated instances showing significant and steady progress toward the ability to develop very short term predictions for small locales (battlefields). Improvement is needed with respect to defining a basis for comparisons between modeled and measured data—that is, there is need to define a better metric for what is good enough for Army applications.

BED has seized a clear leadership position in the examination of effects of atmospheric turbulence, especially at or near the surface of Earth and in urban environments. A fundamental approach to examining these effects is key for understanding sound propagation in the battlefield (e.g., shooter location), updated accuracy of long-range artillery, effects on small robotic flyers (especially near buildings), the mixing of aerosol particles (smoke, fog, hazardous particles) into the atmosphere, and effects on optical signals. BED has demonstrated year after year continued advances in all of these areas, although there have been some concerns about nuances of the physics being modeled. BED has, however, leveraged a long series of experiments, mostly at its White Sands, New Mexico, facility, which are largely unique and provide a solid basis for validating the models.

Related to this work is a series of projects addressing atmospheric effects on nontraditional imaging techniques, particularly those involving terahertz radiation sources and using polarimetric signatures. This research has been making continued and good progress over the past couple of years, but it has been to some extent paced by the available hardware. The quality of the data gathering and the well-defined motivation are particularly important. The techniques are not ready for system deployment yet but are moving in that direction. BED should continue efforts to propose possible operational concepts to leverage this work, particularly as advances are made in AC&CSD to develop tactical HPC systems with the computational power needed for these applications.

## OPPORTUNITIES AND CHALLENGES

### Potential Crosscutting Issues

Prior ARLTAB reports have suggested several technology issues that have cut across multiple ARL directorates, but with particular impact on CISD. Examples include advanced computing, networking (especially ad hoc), information fusion, information security, system-of-systems analysis (SoSA), prototyping, and verification and validation. The current report notes the commendable start of efforts that address several of these issues (advanced computing, information fusion, networking). Others, such as information security, SoSA, and V&V, remain issues that could benefit from more crosscutting activities. In addition, however, several new areas surfaced in the 2009-2010 reporting period that may also qualify for ARL-wide consideration:

- *Microrobotics:* The need for surveillance, especially at the squad level, has continued to explode, and the introduction of smaller and smaller platforms is continuing to offer new opportunities for deployment. CISD is potentially at the heart of such systems, which involve networking, information fusion, and high-performance onboard image processing—obvious candidates that would engage ISD, NSD, and AS&CSD, but the ability to carry weather detectors and/or to be influenced by micro weather events clearly is also relevant to BED. New capabilities such as swarming and electronic warfare (jamming) will also clearly involve not only CISD but will also interact with SEDD in the development of new sensors compatible with limited resources, and with the Vehicle Technology Directorate (VTD) when computing can simplify platforms.
- *Power:* Energy consumption has become a first-class design constraint on almost all Army platforms, especially as more and more functionality is done with computing.
- *Prognostics and diagnostics (platform-based fault detection and reconfiguration):* The increase in platform complexity and the increasingly rapid schedule of introduction, deployment, and retirement mean that the average soldier who must deal with complex equipment barely has time to learn to use a new system, let alone to become expert enough to be able to repair or reconfigure it. Computing must take a central role in the automation of platform-based fault detection and reconfiguration, but it must do so in ways that are compatible with the platforms and that simplify the soldier's overall workload. CISD needs to be involved both in platform-based fault detection and reconfiguration and in remote real-time data mining, parameter extraction, trend analysis, and real-time modeling.
- *Biomechanics:* Although CISD does not have as central a role in biomechanics as exists in HRED, there certainly will be a need to develop and then support significant modeling activities, particularly using HPC expertise, facilities, and resources.
- *Acoustics:* Already a strong area in CISD's research portfolio, acoustics will increase in importance as additional sensors and additional laboratories such as HRED's Environment for Auditory Research (EAR) come online and require modeling support, data visualization, and correlation with atmospheric effects.
- *Modeling and computational science:* This area clearly overlaps multiple components of CISD's charter, and it remains, through several ARLTAB reviews, an identified area for crosscutting activities.

The issue of identifying potentially disruptive technologies that might radically change the problems which face the Army (such as the rise of asymmetrical warfare and IEDs) and the way in which the Army needs to leverage technology to respond to them are of ARL-wide importance. However, in the very fast moving technologies that are the realm of CISD, change—presenting both threats and opportunities—probably occurs faster than in other directorates. Thus each of CISD's divisions, and CISD as a whole, may benefit from an explicit recognition of the potential of such technologies and the development of a formal mechanism to help identify critical technologies in a timely fashion.

## Challenges in Networking

The previous report of ARLTAB commented favorably on the potential created by the formation of the Network Sciences Division and the related Mobile Network Modeling Institute. At the time of that assessment, ARL indicated that this development was in part an outgrowth of prior ARLTAB assessment findings which stated that a variety of issues associated with mobile networks had risen to be of crosscutting importance to ARL. The issues that ARLTAB had discussed as being important to the Army included network security, ad hoc wireless networks in particular, system prototyping, and model validation and verification. The structure of the then-new NSD focused on three levels of the problem: tactical network assurance, networking sciences development, and sustaining base network assurance. This structure continues to represent an R&D capability that, if developed appropriately, could have significant impact on a wide range of real current and future Army problems.

One example of an R&D achievement in this area is an attempt to use small, covert perturbations of a signal between two wireless nodes to increase the probability of identifying a valid node and likewise to increase the probability of identifying a node introduced into a network for nefarious purposes. This work won Best Army Conference Paper of the Year and Invention of the Year awards.

However, there are still challenges to the fulfillment of these capabilities in operational systems. Networking is still a new area, but it would help both the evaluation and the applicability of the work to have a more careful articulation of the key problems being attacked and of how the research is being directed to address them. For example, the work reviewed in this cycle tended to be divided between strong theory, with the relationship to real Army problems not being crisply described, and work that had a good Army connection but that had lost the connection with networking. The former, theory-related work (on multi-hopping in cognitive networks and statistical interference) was usually good but not necessarily cutting edge, and it often made early assumptions with little perceivable justification with respect to how the work might relate to real applications, especially with relevance for the Army. The latter work (such as that on distributed information quality or component-based routing) had good Army motivation, but it seemed to define networks in a much more abstract sense than that used to establish NSD or the Mobile Network Modeling Institute, and it often seemed to be more closely related to Information Sciences Division problems than to networking issues. This latter work also lacked something that is fairly typical for classical network problems, namely, metrics of correctness and success that can be measured or estimated in a meaningful fashion.

Related continuing concerns, discussed below, about the validation and verification of network models, are along the same lines as those articulated in many previous ARLTAB reports. Standing the Mobile Network Modeling Institute had as one of its goals the creation of a capability to simulate, emulate, and model networks in ways that could shorten the time to do design exploration, prototyping, and deployment. Such models include ones that cover protocols, waveform propagation in the environment, and traffic models. However, there is still not enough effort being made to ensure that these models, especially when run in a multiscale, multilevel, end-to-end mode, are in fact reliable predictors of reality. The suggestion from previous reports continues: CISD should perform joint experimental and modeling efforts using devices such as the Blue Radio to achieve such V&V.

Related to the preceding issue is a concern that there may not be as full an understanding of the state of the art as is needed to address the leading-edge problems facing ARL and to avoid activities that are not as calibrated to the state of the art elsewhere as they might be. CISD should consider continuing to send some of its Ph.D. researchers to top venues and then have them organize ARL workshops at which data sets developed in NSD and the institute can be used to help promulgate the problems on which ARL is focused and to help evaluate whether answers from external research are relevant (much as has been done over the years by the CISD machine translation group). Another suggestion would be that CISD strengthen ties with some leading external research groups such as the Research Laboratory of Electronics at the Massachusetts Institute of Technology.

There is also potential in NSD to implement a practice that is currently employed in BED—namely, the accumulation of unique, world-class data sets from experimental and/or modeling efforts and the documenting of these data sets in ways that will allow them to be useful both to ARL in its future efforts and to the larger R&D community.

### Challenges in Battlefield Environment Studies

The research portfolio of the BED has for years been an exemplar of a good balance between modeling and experimental efforts—especially, for example, in testing in realistic theaters such as at the world-class facilities at White Sands, New Mexico, and in multidisciplinary efforts such as the use of HPC. For the most part this continues, but with some challenges as new areas (such as aerosol dispersion or ultrasonics) are entered and more complex environments (such as urban areas, with turbulence) are attempted. These challenges lie largely in the articulation by researchers of their understanding of what it takes to validate a new model, and with mapping out in the long term how the results of such research might be deployed. There is, however, an excellent roadmap in place for traditional weather-related work, and BED should consider fleshing out in that roadmap possible alternatives for these new areas.

### Challenges in Decision-Aiding Systems

The work discussed above about social network analysis clearly is key to fusing information and aiding the warfighter in making decisions. There were, however, still challenges in elevating and applying research in the area. In the current review cycle, several projects exhibited such challenges. First, related to the problem of managing and searching huge knowledge bases were some initial efforts, reported in 2010, at using a new software paradigm called Hadoop (an implementation of the MapReduce programming model) to solve the entity resolution problem—the problem of disambiguating a name from many possible matches. Hadoop was started by Google, Inc., to attack the same type of massive data-intensive applications that are liable to occur in SNA problems. The problem chosen for study is an embarrassingly parallel problem well suited to this approach. In addition, Hadoop has been adopted by the Army Intelligence Security Command (INSCOM), and so using this approach will simplify integration into potential future customer systems. The work was a reasonable initial project for learning about the Hadoop technology, but it was not about research into methods for entity resolution; rather, it was an evaluation of some existing tools for the entity resolution problem, making use of two public databases containing the names of movie actors.

As appropriate as the approach may be, the current project had some significant challenges. As an evaluation of existing software, the overall problem was not well formulated. For example, how would results on these public databases translate to databases of interest to INSCOM? The latter are likely to be much larger and may also contain more errors or have more complex entities (indeed, a separate CISD presentation explained that, in Iraq, identifying a particular individual may require both the person's name and where that person sells in the marketplace). Without a simple analytic performance model to reflect a scaling of the database size, the initial experiments cannot be placed in context and can only suggest, not predict, the performance against larger data sets. The work was not sufficiently connected to the tactical needs of the Army or to other, related work in the broader intelligence community, and the project needs to put its work in that context. The project needs to have a clearly stated objective that is consistent with the mission of ARL. This is important technology—CISD should develop a clearer set of objectives and an experimental design that addresses those objectives, along with closer interaction with both INSCOM and the broader intelligence community.

Another example with respect to challenges in decision-aiding systems was an attempt to characterize team decision making (i.e., a human network) experimentally as a function of information loss and delay due to data network issues; an existing platform called ELICIT was used to represent information sources, servers, and decision makers, and validation of agent-based experiments was done through human-in-the-loop experiments. The fundamental concept behind this work was sound—that is, determining the impact of variations in network quality of service on decision making is an important Army need. However, without care in performing such human-computer network experiments, the actual value to the Army could be limited. In particular, using just delay and loss measures in the data network models seem limiting, especially in terms of parameters that are relevant to how humans interact with such networks. Better coordination with HRED and the Communications-Electronics Research, Development, and Engineering Center may be able to help with realistic assumptions. However, the real problem today is collaborative decision making (the human side of the networks), but it was not obvious how the results would relate to parameters such as correctness of decision or how the results would be validated other than by comparison. CISD should consider introducing U.S. Army Training and Doctrine Command-validated behaviors into research and interacting with the Joint Experimentation Directorate.

## Challenges in Robotic Autonomy

A growing asset for soldiers is the use of small, robotic platforms to go where there may be significant unknown danger. Key parts of making such platforms usable, especially in complex urban terrains, are communication between the platform and the troops and navigation of the platform in ways that permit a wide range of semiautonomous behaviors. Over the past few years, CISD has presented to the panel the results of a series of reports on related projects from multiple divisions within CISD. Given the criticality of the problems and the potential value added by real solutions, the continued effort is commendable. However, there are challenges, primarily in developing system concepts that are realistic and might be fieldable. (Both of these points are examples of the potential usefulness of a more consistent systems engineering focus, as discussed below.)

One example of such challenges is a project looking at the deployment of robots to form a dynamic network where various platforms may be out of the line of sight of the troops (e.g., inside a building on the other side of corridors). The problem posed was clearly a difficult one, but it suffered from an assumption that a map existed at the beginning and from questions about radio-frequency propagation and map construction, especially in the three-dimensional environment represented by a building. Also, one would expect that topologies that represent richer than a minimum connectivity would be more valuable in a warfighting environment where intermediate relays may be destroyed or go off-line.

A related project involves indoor navigation in a Global Positioning System-denied environment using a combination of out-of-building sensors and dead reckoning based on a simple inertial navigation unit tied to a soldier's foot. The project's first year of work was reported to have been focused on the capabilities of a simple inertial measurement unit (IMU). The panel thought that the challenge was not as much in the actual work or approach (both seem to be of high quality) as in operational concepts issues: What happens when a soldier is not walking but crawling? How are initial locations established? How can external sensors help? Many of these concerns could be mitigated by some coordination with combat forces personnel.

Another related project was one whose goal is an algorithm to estimate a robot's position and movement by combining epipolar lines from images with IMU data, with demonstration on PackBots. This is an excellent problem, with direct application to a number of Army problems. However, there is a potential challenge related to how this research might transition to a relevant deployable system: What aspects of IMU-driven navigation would be improved (and by how much)? What kind of processing needs to be onboard the platform to be usable in a real-time setting? What are the lower-level details of the filters assumed?

## Challenges in System Engineering

As noted in prior ARLTAB reports, it remains a significant challenge across CISD to ensure that even in relatively basic research programs a good understanding is formed about how potential systems that might be developed out of such research might be deployed and used in real Army scenarios. A small amount of systems engineering early in many programs could help avoid paths to systems that, even if successful, would be difficult to deploy in real-time systems or would have some obvious characteristic that would make them impractical. And, conversely, a small amount of systems engineering early in many programs could provide insight into alternatives that would mesh much better with practice. The same systems engineering focus would also help enable early comparison of research goals with expected roadmaps for established technologies and help prepare realistic statements of the potential gains from the new technologies being researched. It is insufficient to pursue the development of technologies that are better than those of today, but which may be potentially only on a par with what is expected from the natural progression of technology.

## Challenges in Evaluation, Validation and Verification, and Experiment Design

Another general comment from prior ARLTAB reports that remains a challenge across CISD involves testing and evaluation for experimentally driven programs and the validation and verification of models—validating that models developed during research programs actually reflect reality and verifying that the codes or systems that are constructed are in fact correct implementations of the models. There are research areas such as machine translation in which a V&V mind-set has become central to the research process, and others with apparently little such focus. In still others, particularly projects involving complex computations, there continues to be a tendency to develop stand-alone codes, without any clear approach articulated as to how to ensure that both the algorithm modeling the physics and the implementation of that algorithm are correct. A tendency to believe the machine is evident, and it needs to be avoided by formal verification.

A key example of a systematic need for V&V is in the networking area, as discussed above, especially in the modeling area. The signal-propagation models used for such systems as soldier-mounted mobile networks or sensor networks must match the actual close-to-the-ground physics of the battlefield, while assuming the kinds of transmission waveforms that are liable to be used. The traffic patterns used to drive studies of inherently low power protocols must reflect reasonable configurations, particularly in mobile cases, or the results are potentially misleading.

If done right, solving the V&V dilemma can, as a side effect, provide significant long-term benefit for future research, both in ARL and in the larger community. BED has for a long time taken care to save the data sets that come out of V&V experiments, and that has provided a rich knowledge base to fuel future work. A formal process for doing the same in other areas, such as networking, will possibly have similar long-term value.

The previous ARLTAB report also discussed another emerging general need: that of performing sophisticated analyses on experimental data. Such analyses involve both classical statistical computation and, perhaps more importantly, information extraction from large and often unstructured data sets. Data mining has emerged in the commercial world as key for applications ranging from determining personalized online purchase preferences to performing portfolio analyses. In this 2009-2010 review cycle, CISD described several projects to begin such efforts, including work on Hadoop—the technique that has grown out of the Web search and services world to use large numbers of computers in an organized fashion to perform very fast unstructured searches on queries that are generated on the fly. This work is a valuable learning experience, but it is not research yet. Questions on what kind of data sets are relevant and, more importantly, on how their size must scale, at the tactical versus operational versus strategic level, were not articulated, and so questions such as where the technology works or breaks are largely unanswered. (This is also an example of the need for a systems engineering perspective, as discussed earlier.)

A challenge related to those discussed above, but somewhat different from those articulated in the past, became evident during this review cycle. More and more research projects are faced with multidimensional design spaces with large numbers of possible parameter values, leading to combinatorial explosions in the number of cases to be explored. In multiple research projects observed by ARLTAB, CISD often applied ad hoc approaches to determine which subsets of these design spaces would be explored and how the results from one set of explorations would be used in the next set. This was true for both model-driven work and experiment-driven work. Some in-house expertise in experiment design could prove invaluable both in reducing the resources needed for the explorations and in raising confidence that more near-optimal solution points can be found.

### Challenges in Work Flow Analysis

Prior sections of this chapter comment favorably on the high quality of the work on developing a process for transforming large numbers of paper documents in non-English languages into information stores of real use to analysts. Other research within CISD also has a similar focus on automating what today are people-intensive processes. Independent of the usually high quality of the technical work involved in the automation process itself, there seems to be a need to better define and track metrics that adequately reflect the reduction in the human workload and/or the extension of human experts—productivity that results from employment of the automated work flow. The general question of how errors propagate through the system could benefit from more thought, as could an articulation of plans for completing the research and transitioning the technology. The Defense Advanced Research Projects Agency, it should be noted, is not a transition target. Many of these issues are of the kind that a systems engineering viewpoint would help, in this case as possibly found in HRED.

## OVERALL TECHNICAL QUALITY OF THE WORK

For this 2009-2010 review, the Board was asked to comment on several criteria. The first asks if the scientific quality of the research is of comparable technical quality to that executed in leading federal, university, and/or industrial laboratories both nationally and internationally. As in prior years, the answer is generally affirmative for CISD, which has exceptional expertise in selected areas such as weather, the use of quantum effects for fundamentally new imaging systems, and the leveraging of machine translation technology. Collaboration with external research entities, especially universities, again continues to be widespread throughout the directorate, although concerns continue about how much of the research that is reported had been done by or transferred to ARL, and to CISD in particular.

Although the scientific and engineering staff are, on the whole, conducting and publishing quality research in a number of areas, a continuing concern is that there does not seem to be much involvement by staff members in leading scientific societies and organizations. Promoting such involvement should give rise to more scientific recognition and stature for the research staff, make them more aware of the state of the art in other groups, and make ARL more attractive to new Ph.D.'s. In addition to encouraging participation on review panels and editorial boards, consideration should be given to encouraging researchers, especially newer members of the staff, to help in organizing and hosting workshops on issues of relevance to ARL. Where possible, access might be provided to repositories of data sets that represent experiments of relevance to the topics of such workshops.

The second criterion on which the Board was asked to comment questions whether the research program reflects a broad understanding of the underlying science and research conducted elsewhere. The answer here is essentially the same as in the previous ARLTAB report: the conclusions for various projects are mixed, with the areas mentioned above being exceptional. Success is especially evident for areas that have emphasized testing and evaluation, such as weather and machine-based language translation. However, in other areas such as data mining, where there is neither a history of prior internal projects nor collaborations in that area with others outside ARL, there is a distinct drop-off in an understanding of other work or the availability of existing program packages.

In terms of the third criterion—whether facilities and laboratory equipment are state of the art—the answer is again the same as in prior years: a largely solid "Yes." In many cases, it is not necessarily the equipment but the planning for using that equipment more effectively that could benefit from additional attention. There is a continuing concern about using the appropriate numerical models, especially within the Mobile Network Modeling Institute.

The fourth criterion addresses the qualifications of the research team versus the research challenges. With just a few exceptions, the match seems to be adequate. In addition, the aggressive hiring of significant numbers of new Ph.D.'s in all divisions and the continued encouragement of Ph.D.-level work by current employees are a very positive indication. The hiring of a social scientist to lead a major CISD research group is an indication that ARL understands the need to grow expertise that is truly multidisciplinary. The success in hiring, given the long timescales that seem to be enforced on the hiring process by the bureaucracy, is remarkable. Creatively using postdoctoral research positions to evaluate new Ph.D.'s and giving them insight into the kinds of opportunities available at ARL should be continued.

CISD research generally reflects an understanding of the Army's requirements, although this focus is sometimes lost on projects of a more theoretical bent, such as some in the networking area, when a project needs to attempt transition from project formulation to the selection of data set characteristics that should be representative of Army scenarios.

The next criterion deals with the structure of programs in terms of employing the appropriate mix of theory, computation, and experimentation. The results here are again mixed. In cases where projects effectively take advantage of ARL's outstanding test facilities and weave in a feedback path that validates theory and drives more robust algorithm and system development, the results are usually strong, with obvious opportunities for transition. In other cases, where the use of facilities or the feedback of validation results is lacking or weak, effectiveness appeared less than optimal. The long-running issues related to V&V still remain, with the emergence of intelligent experiment design during this review cycle as something that, if improved, might enhance both the quality of results and the efficiency of achieving them.

As indicated in prior assessment reports, the CISD management and research teams remain responsive to ARLTAB's recommendations. CISD has instituted significant organizational changes, especially in the networking and HPC areas, that seem to be directly focused on alleviating problems that ARLTAB had commented on in the past. The NSD and associated institutes and other initiatives are a prime example of this responsiveness, in their being organized around an end-to-end focus on networking in the large. The reorganization of AC&CSD to address the growing appearance of HPC-like functionality in everyday battlefield computing resources is another example. Further, within the portfolio of research projects there have been positive, significant changes, with projects dropped in areas that ARLTAB suggested were redundant or behind the state of the art (such as nanoelectronic devices), and new projects introduced in areas where there was evidence of significant Army mission-relevant potential (such as embedded HPC, networking problems, and bio-inspired applications). This responsiveness has even shown up in the way that individual divisions, especially BED and ISD, report out their research portfolios at the panel reviews.

There is, however, still room for improvement, especially in articulating both divisional and overall CISD strategic plans and the rationale behind how the research portfolio is adapted to customer pressures while maintaining a solid and relevant basic science capability. There has been improvement, but it is not consistent across divisions, and the research portfolio does not roll up as crisply as it could to the strategic plans. An emphasis on defining the core long-term, relevant scientific problems and an articulating of short versus long-term strategic goals would help to maximize the value of CISD's research portfolio to the Army. A suggested additional metric is how CISD's customers perceive the value of their collaborations with CISD, with a related discussion of how expectations and requirements are developed in light of such metrics.

As noted in the previous ARLTAB report, although there seems to be a significant number of collaborations of various sorts, it is often not clear how those collaborations interact with ARL programs (versus simply being funded grants), and what part of the results reported from the collaborations are due to ARL versus external researchers and contractors. This matter is important when trying to judge the overall level of expertise of the ARL staff.

The final criterion asks whether a reasonable part of the ARL portfolio is being applied to breakthrough innovations as opposed to incremental progress. Although it is unclear what is reasonable, it is very clear that potential breakthrough innovations are being fostered in CISD. The Quantum Ghost Imaging work discussed above is one example presented during this review cycle.

# 3

# Human Research and Engineering Directorate

## INTRODUCTION

This chapter is based on the visits by the Soldier Systems Panel to the Human Research and Engineering Directorate (HRED) at Aberdeen Proving Ground, Maryland, on June 9-11, 2009, and July 13-15, 2010, and on examination of written materials provided in association with those visits. During those visits the panel received briefings on substantial portions of nonclassified HRED work, mostly in the 6.1 (basic research) to 6.2 (applied research) categories. This chapter provides an evaluation of that work, recognizing that it represents only a portion of HRED's portfolio.

### Five Broad Areas of Research

HRED research falls into five broad areas:

1. *Human Robot Interaction (HRI):* This program deals with the integration of robotic devices into the military and, to some extent, into broader civilian life. These researchers seek to understand how a soldier or group of soldiers can work with autonomous or semiautonomous machines at scales from hand-carried devices to vehicles.
2. *Human System Integration (HSI):* This program models the personnel requirements of Army systems, including workload calculations, skill levels demanded, interface designs, and automation. Much of this work is carried out in the context of the Manpower and Personnel Integration (MANPRINT) modeling system.
3. *Neuroscience:* This work focuses on the use of neuroscientific methods to monitor and enhance solider performance.

4. *Social and Cognitive Network Science:* This research investigates the human behavioral aspects of networked operations. Distributed communication and decision making within and between groups constitute a particular area of interest.
5. *Soldier Performance:* This area is concerned with the human factors that impinge on the design of military systems, examining how those systems can be best configured for a human operator.

Table A.1 in Appendix A characterizes the staffing profile for HRED.

## Directorate-Wide Themes

HRED has a vast and very important mandate: to understand the functions of the human-in-the-loop in a wide range of Army systems. The most sophisticated sensors, weapons, and information systems will not deliver their full potential if they are not well matched to the capabilities of the humans using them, in the conditions under which they are intended to be used. This human-in-the-loop domain includes a wide range of research topics, from basic to applied. Perhaps the fundamental challenge for an organization like HRED is how best to select some subset of the nearly infinite number of possible topics for study.

The directorate's response to this challenge can be understood by considering the nature of HRED. Two visions, not mutually exclusive, compete to shape HRED's activities: Is HRED intended to make significant contributions to the peer-reviewed scientific enterprise in the manner of a university laboratory? Is it supposed to be applying the basic science of others to specific issues raised by its Army customers? Presumably, the answer is "yes" to both questions, but those goals live in necessary tension with each other. Customer-based, applied work is of obvious importance, but the results will often be too specific to be interesting to the broader scientific community. Basic science projects must proceed with the understanding that they might fail or, perhaps more typically, that they will produce valid, statistically significant results of no apparent near-term use to the Army. The accumulation of such results is the required cost for those much rarer basic science breakthroughs that transform practical systems and operations. In a perfect world, resources and personnel would be available to prosecute all of the interesting and valuable projects from the basic and applied realms. In the real world, HRED must continually wrestle with the balance of its allocations of time and money.

The issues surrounding the selection of research topics seem to be handled more successfully in some branches of HRED than in others. There are selection mechanisms in place. For example, at the large scale these include Army Technology Objectives (ATOs)—project proposals must describe how the project contributes to formally defined ATOs. At a finer grain, individual research proposals may be reviewed by Army Research Laboratory (ARL) fellows, experts in their scientific domains, whose appraisals of proposed projects are provided to the ARL Director, who decides whether to allocate to proposed projects discretionary funds for the initiation of research. The effectiveness of this rather complex and bureaucratic system varies across HRED. Leaders with clear vision can use the system to shape effective research programs. In other cases, the system may overwhelm the vision.

One means of alleviating, though not eliminating, the problems of project selection is to increase resources. The Collaborative Technology Alliances (CTAs) in Cognition and Neuroergonomics, in Network Science with the Computational and Information Sciences Directorate (CISD), and in Robotics with the Vehicle Technology Directorate (VTD), are important mechanisms for increasing the capability to contribute to fundamental science in these areas.

## CHANGES SINCE THE PREVIOUS REVIEW

Since the previous ARLTAB review,[1] HRED leadership has stimulated the activity of the HRED community. Staff has grown, and there has been significant turnover in personnel, with a resulting influx of early-career talent and energy, to the benefit of the directorate as a whole. There is an increased emphasis on the impact of HRED work on the broader scientific community. This can be seen in increased publication in peer-reviewed journals, attendance at basic science conferences, and collaborative work with members of the university research community.

Significant new HRED facilities have begun to demonstrate their planned functions, including the Cognitive Assessment, Simulation, and Engineering Laboratory (CASEL), the Environment for Auditory Research (EAR), and the Open EAR. Others, such as the Soldier Performance and Equipment Advanced Research (SPEAR) facility, are in development.

At the time of this writing, the Army's Simulation and Training Technology Center in Orlando, Florida, is in the process of becoming a part of HRED. This move brings more than 35 technical staff personnel and their research programs under the HRED umbrella. Significant opportunities for synergistic new research co-exist with the challenges of integrating the group into HRED.

## ACCOMPLISHMENTS AND ADVANCEMENTS

### Human Robot Interaction

Robots continue to be important tools for soldiers in a variety of contexts. Consequently, research in this area is highly relevant to both near-term and long-term Army mission goals. In general, many aspects of the research have improved since the previous review. HRED has successfully identified a number of key problems in this domain. The HRI group clearly realizes that it is not working on traditional robotics problems and that it must pay close attention to soldier-robot interaction, which is important for long-term applicability of the research. Progress was demonstrated on multiple fronts in this research area, particularly in the work incorporating real robots and addressing important field-motivated questions, and in increased consideration of scenarios involving soldiers controlling more than one robotic platform at a time. Similarly, research on alternative modalities for soldier-robot communication and adaptive automation are well motivated by concerns faced by actual soldiers in the field. Another area of substantial improvement is the increased use in research of the actual robotic platforms currently deployed in the field. The HRI Robotics Collaboration Army Technology Objective Capstone Experiments represent a good example of meaningful, warfighter-motivated research evaluated in a realistic field setting. This is the kind of research that HRED is uniquely positioned to do, making use of real Army operators testing field-ready technology.

### Human System Integration

The HRED Human System Integration group develops models, tools, and methods to support the assessment and evaluation of warfighter systems. The group is continuing to improve the usability of its models and tools (e.g., the Improved Performance Research Integration Tool [IMPRINT]), and its use

[1] National Research Council. 2009. *2007-2008 Assessment of the Army Research Laboratory.* Washington, D.C.: The National Academies Press.

of these tools to support Army applications is commendable. Overall, HRED has the opportunity to be at the forefront of research in this area.

The IMPRINT model development effort continues to reach out to meet the needs of a wide range of users. Users can now develop their own plug-ins and post these on the IMPRINT Pro Online User Community Web site, a SharePoint site. This is very useful for researchers, industry, and Army users. IMPRINT also incorporates existing modules (e.g., the Sleep, Activity, Fatigue and Task Effectiveness model—SAFTE) that have been validated with other Department of Defense (DoD) models or tools. The mission-based testing and evaluation group has demonstrated a clear track record of successful application of IMPRINT in conjunction with field evaluation methods. An outstanding example was provided by the project's applying domain and mission analysis techniques, IMPRINT modeling, and human-in-the-loop evaluation in close coupling to inform the design of the Joint Light Tactical Vehicle. The analysis and modeling methods developed by this group provide an effective and useful roadmap for how computational models can be used to inform design. In a rather different application, an activity performing the testing and evaluation of a new financial system applied analytical tools normally used in evaluating weapon systems to a large, office-management financial system. The work appears to be well grounded and well tailored for the analysis of complex systems (e.g., a usability matrix that has been established for reliability).

Recent initiatives by HRED to incorporate plug-in models into IMPRINT are commendable. Different subsets of IMPRINT users (both within and outside DoD) have expressed requirements for specific functionality in using this important soldier-workload-assessment tool. This flexibility is especially important when using the IMPRINT tool to assess proposed major changes in equipment design, such as determining the appropriate number of crew members required to operate a new vehicle in a variety of operational scenarios. HRED's initiative to incorporate the well-established SAFTE model into IMPRINT will provide a basis for subsequent trials of incorporating other plug-in models, such as the Navy's SeaState, the U.S. Air Force Human Systems Integration module, and the Multimodal Information Design Support module.

The HSI team actively and admirably serves as a bridge between the laboratory and the field, as demonstrated by its effective participation in the ARL-Field Assistance in Science and Technology (FAST) Program, in which HRED representatives interact with soldiers in the field (e.g., in Iraq) and communicate to ARL equipment needs expressed by the soldiers. The FAST Program contributes significantly to what soldiers, commanders, and military units deployed in the field really need—a two-way conversation with the Army's research and development (R&D) laboratories to enact quick fixes in the field and to help identify what new systems and technologies will be important for future battles. The project to apply human factors engineering in Iraq compellingly illustrates the value of the deployment of HRED personnel to theater where they can obtain a first-hand understanding of the problems faced by ARL end users (i.e., soldiers). Visiting soldiers downrange in the field is an excellent way to gain the goodwill and respect of those users. It may also be the best place to obtain feedback on ARL prototypes (e.g., chaps, or leggings designed to protect soldiers from contact with blood). Participation by the human factors group in the FAST Program should continue to be supported.

## Neuroscience

In 2009, the National Research Council (NRC) completed a 2-year study designed to advise the Army on opportunities for neuroscience research.[2] That study identified 17 key suggestions for Army research in this area. Of necessity, those suggestions spanned the Army's many laboratories, but at least 4, and perhaps as many as 8, were relevant to the U.S. Army Materiel Command and to ARL in particular.

The current neuroscience group at ARL, although still quite new, has clearly begun to make headway on the three recommendations most relevant to ARL. At a technological level, the group has begun to develop core competencies in electroencephalogram (EEG) measures of soldier performance, in functional magnetic resonance imaging (fMRI), and in the interaction of fMRI and virtual reality. The group also has focused on improving soldier-system interfaces by taking into account neurobiological constraints on information processing, an area coming to be called neuroergonomics. The group has begun to make some headway in characterizing individual variability at the neural and behavioral levels—another key recommendation of the 2009 NRC study.[3] This constitutes solid progress toward the long-term integration of neuroscience research into the Army's portfolio. It is worth noting that this aspect of neuroscience research is distinct from the medical neuroscience work performed in other DoD laboratories.

The emerging neuroscience group at ARL has proceeded as a model of program development. Clearly set goals and innovative experimental programs mark out a young program that is on track to produce highly significant and Army-relevant 6.1 and 6.2 research. HRED has recruited and motivated an effective neuroscience group of early-career scientists whose members are well trained, having come from strong graduate and postdoctoral programs. Overall, the HRED neuroscience group has reached a level of quality that would allow it to fit in well as a solid, small neuroscience group at a reputable research university.

The neuroscience group is commendable for its focus on significant aspects of neuroscience that can be translated into the real world of the battlefield. There is a strong focus on Army-relevant psychophysics and neuroscience and on multimodal integration, and there is a recognition that interindividual differences will play an important role in sensory processing, integration, and cognition. The neuroscience group has a healthy respect for real-world complexity conjoined with its policy of keeping translational goals squarely in view.

The single most exciting accomplishment by the ARL neuroscience group during this assessment period was its development of single-trial-based, Army-relevant paradigms for brain-behavior analysis. The demonstration that an independent component analysis (ICA)-based EEG can be used at the single-trial level to explain "Shoot/Don't shoot" behavior was a tour de force. The group demonstrated that classical psychophysics could be extended both to EEG and to Army-relevant tasks. The neuroscience group should be encouraged to explore additional tasks like these that relate single-trial behavior to brain activity in stylized but relevant tasks.

The publication rate of the group in peer-reviewed journals is good, and continued publication in Tier 1 journals should be encouraged. It is likely that the group will be highly productive in the years to come. There is no reason that the HRED neuroscience group should achieve any less than the publication rate of a Tier 1 group at a major research university.

[2]National Research Council. 2009. *Opportunities in Neuroscience for Future Army Applications*. Washington, D.C.: The National Academies Press.
[3]Ibid.

## Social and Cognitive Network Science

As the previous ARLTAB assessment report[4] indicated, at ARL generally and in HRED in particular, there are major opportunities within the network science area to address the cross-disciplinary problems that bear on individual, team, and large-group performance in distributed, networked environments. These efforts would be built on HRED's existing and unique capabilities and resources. The report also noted that the program seemed to be defined to encompass the entire range of physical, information-based, cognitive, and social phenomena emerging from the introduction of network-centric operations as they might influence support for warfighters. Since that review, the program has produced a more circumscribed account of its domain of research. Specifically, its major purpose is to improve distributed collaboration and decision making in warfighters' complex networked environments by using cognitive science, computer science, and social network innovations.

There have been some accomplishments over the 2 years since the previous assessment. These include a number of important steps that the ARLTAB report had recommended. First, it had been noted that the breadth and complexity of the program's purpose demanded a sufficient research staff. Two Ph.D. researchers were hired in the past year. Both have experience studying teams and networks. These additions should be helpful not only in boosting the productivity of the program, but also in further refining its focus while integrating it into the greater community of network research activity both within and outside ARL. Thus, a closely related second accomplishment is the undertaking of more collaborative work. Given the rapid growth and progress in network sciences on the one hand and the pace of technological change in social media on the other, it is important for researchers in HRED's program to work collegially with other scientists in this field. Besides involvement with a Multidisciplinary University Research Initiative (MURI) and a large network science collaborative program directed by ARL's Computational and Information Sciences Directorate, the establishment of the Network Science CTA with Pennsylvania State University takes a positive step in this direction.

A third promising indicator has to do with improved financial support for the program. This is evidenced not only by the newly awarded CTA but also by seed money in the form of a Director's Strategic Initiative (DSI) to generate new research efforts aimed at improving the understanding of the human dimension of network science. However, the DSI project at HRED has been less successful than desired by HRED at bringing in outside funding for the research.

Several research projects in the agenda of the social and cognitive network science program have been brought to completion, fulfilling another recommendation from the previous ARLTAB report. These include, for instance, a laboratory study of distributed dyadic interaction and the effects of network delays on pairs' communication outcomes, as well as a qualitative linguistic study of misunderstandings that arise in communications among members of cross-cultural teams.

## Soldier Performance

### Key Facilities

Major effort in the area of soldier performance has gone into the creation of two facilities whose establishment represents significant recent accomplishment:

[4]National Research Council. 2009. *2007-2008 Assessment of the Army Research Laboratory.* Washington, D.C.: The National Academies Press.

1. *Tactical Environment Simulation Facility:* This facility includes two major research features: The first is an immersive environment simulator that integrates visual and auditory displays with an omnidirectional treadmill (ODT) mobility platform that enables test participants to have natural human locomotion through a virtual environment. The second is a hostile environment simulator, an acoustic chamber containing a high-intensity audio system capable of producing sound-pressure levels up to 155 dBP (e.g., weapons-firing noise). Some validation studies with the ODT show its potential to be used in well-controlled experiments with dismounted soldiers progressing over nonlinear paths—for example, studies of load carriage, exertion, and neurocognitive variables.
2. *Environment for Auditory Research (EAR):* Since the previous ARLTAB report, HRED's auditory research staff has been engaged in finishing the construction of the four acoustic rooms (distance hall, listening laboratory, dome room, and sphere room) that constitute the EAR facility. The research staff has conducted measurements in two separate experiments that helped to verify the properties of those rooms and to establish their baseline. As noted in the previous ARLTAB report, the EAR facility presents remarkable potential for both in-house and joint research with collaborative agencies and other researchers. The leadership of the EAR facility recognizes the desirability of making the EAR available to outside researchers and has taken some steps in that direction.

## Research in Soldier Performance

HRED conducts a wide variety of specific research in the area of soldier performance. Examples include the following:

- *Auditory Hazard Assessment Algorithm for Humans (AHAAH):* A notable accomplishment in sensory research is the decades-long, high-quality basic and applied auditory research done by some but not many HRED scientists. The AHAAH is a superbly developed and validated mathematical model of the human auditory system that predicts hazards from any free-field pressure; it can display visually the damage process as it is occurring. ARL should lead the way in promoting HRED's contributions to what is likely to become an international standardization of auditory damage risk criteria— especially that threatening soldier hearing.
- *Sensory Research:* The soldier performance program has a variety of projects in sensory psychophysical research. HRED has engaged in basic and applied research on the use of tactile displays to augment overloaded visual and auditory channels. Recent work on the sensitivity of the head to tactile stimuli should be published as a contribution to the basic science on the topic. Some progress was made in characterizing the information that could be conveyed through publications at a later date, since this work is not yet ready for publication.
- *HRED and Army Medical Training:* The HRED field office located at the Army Medical Department Center and School at Fort Sam Houston, Texas, has been assisting the center in identifying soldier performance issues that affect rates of retention (graduation) and academic attrition (failure and dropping out) for the Health Care Specialist (MOS 68W) training course. The work is impressive. The HRED team at Fort Sam Houston is conducting a comprehensive sequence of research, applying qualitative data (focus-group questionnaires and interviews), modeling preselection test scores (e.g., Armed Services Vocational Aptitude Battery), and collecting empirical data on class performance. Additionally, the HRED team at Fort Sam Houston began feasibility evaluations of two academic feedback tools for students and faculty. The team evaluated a program

for Personal Academic Strategies for Success (PASS) as a student's self-evaluation tool, and an Academic Class Composite Tool (AC2T) to inform instructor personnel as to where improvements are needed in the courses that they offer. Results of the PASS and AC2T projects are preliminary, and so it is too early to judge their effects.

- *Traumatic Brain Injury (TBI) and Post-Traumatic Stress Disorder (PTSD):* At Fort Sam Houston an ongoing research protocol to assist in the early identification of the presence of mild forms of traumatic brain injury and perhaps accompanying post-traumatic stress disorder, described for the panel in 2009, will have to move beyond the one-time, opportunistic study to a more programmatic, multistudy approach if it is to become a viable research project. However, because TBI and PTSD are the subject of massive research programs elsewhere, it is not clear that this is an area in which HRED can have a major impact without an appropriate, clearly defined focus.
- *Brain Training for Resilience:* Another HRED medical field office research protocol involves plans to evaluate use of audio-photonic stimulation as a form of neurocognitive brain-training technology to enhance student soldiers' cognitive resiliency, especially in terms of resisting anything that would divert attention from performance during sustained operations. The HRED plan is to determine the effects of audio-photonic stimulation on cognitive performance (automated neuropsychological assessment metric, or ANAM) and academic performance (course grades and pass/fail status), self-reported sleep, mood (e.g., by means of the Profile of Mood States rating scale), and self-reported stress. The goal of the project is to help soldiers perform extremely well during sustained operations. Such a research project could offer significant findings to the Army Medical Department Center and School for its field medical personnel, and it could make contributions to the overall Army program entitled Comprehensive Soldier Fitness, which stresses instilling resilience in individual soldiers and small units.

## OPPORTUNITIES AND CHALLENGES

### Human Robot Interaction

The Army Research Laboratory could be positioned to take a leadership role in the human robot interaction domain. The Army has extensive numbers of robots and of soldiers training with robotic platforms. HRED has begun to make use of these resources, and more extensive capitalization on this opportunity is warranted. It should be possible to collect fairly extensive data on both the learning and the performance of human-robot teams using currently deployed technology. Collecting such baseline data would provide researchers at HRED and elsewhere with benchmarks for measuring improvements in future robotic systems. It would also provide additional information about the exact nature of the needs and challenges faced by soldiers in the field.

There are several points of concern. First, HRED researchers need to improve their contact with contemporary research in this area. Researchers seem somewhat isolated from closely related research being done at universities and at other DoD facilities. Contact with this work is important for several reasons. First, there are technical advances that can be of use to HRED. More broadly, contact helps shape the research questions that actually serve to advance the field. Second, as this research moves into areas that involve traditional human-computer interaction studies, it is important that HRED personnel learn techniques and methodologies from that area rather than trying to apply methods that they already know are inappropriate for the research problems that they face. Third, it is not at all clear that HRED is positioned appropriately to conduct research in some of the areas in which it has engaged (e.g., cognitive robotics). Although engaging with these problems reveals vision and foresight, it is not clear that the full range of required technical knowledge is present in the HRED staff or that the limited resources applied are adequate to make meaningful progress. Fourth, it would be useful to have a centralized mechanism to facilitate information sharing, research review, and discussion among the widely distributed HRED robotics-related researchers. Individuals with limited robotics experience would benefit from interaction with others who have more extensive, ecologically valid robotics evaluation experience.

The HRED HRI team should seek to publish and network in relevant venues, such as the IEEE (Institute of Electrical and Electronics Engineers) International Conference on Robotics and Automation and the Association for Computing Machinery/IEEE International Conference on Human-Robot Interaction. Some members of HRED do so, and other projects would benefit from feedback from relevant peer reviews outside the behavioral sciences.

As noted in the previous ARLTAB review, ARL also can bring to bear significant talent from HRED to address human-system integration, along with robotics-related work in the Sensors and Electron Devices Directorate (SEDD) and the Computational and Information Sciences Directorate. There was little evidence that such cross-directorate work is taking place. Many of the research questions being asked by HRED researchers would be well served by more extensive cross-directorate collaboration, because human-robot interaction is intrinsically interdisciplinary in nature.

## Human System Integration

The HSI group has a unique opportunity to contribute to the broader science of human factors. The human-factors issues that the group is addressing and the methodologies that it is developing within the context of particular customer applications are of general interest to the human-factors community (researchers, educators, and practitioners). One mark of the significance of HRED's work in this area is the impact of IMPRINT on the broader community, which is not appreciated in the community as much as it should be. HRED should continue to collect concrete information about this impact. The information could be obtained in a number of ways: for example, (1) searching for IMPRINT in databases such as Google Scholar, Compendex, or PubMed; (2) surveying users through easily available tools like Survey Monkey; and/or (3) compiling data on the number of plug-ins uploaded by users since capability was made available.

Some of the challenges faced by HSI are related to the resources available to this group. Within the Army materiel development community, there appears to be great demand for the MANPRINT services of HRED. However, the in-house staff is too small to support numerous service requests effectively, especially if the same HRED members are expected simultaneously to advance the state of the art in HSI models and methods. Although effort has been expended on improving the usability and application range of the HSI tools, there also needs to be work on the validity and reliability of the tools and, most particularly, on the extensions and plug-ins for IMPRINT. The current portfolio of projects within the HSI area may be too service-oriented if broader scientific impact is an important goal. This is one of a number of areas in which ARL leadership must consider the balance between fundamental research and work for DoD consumers.

The impact of HRED and the HSI program on new system design is enhanced when the HSI group is invited into the system acquisition process at an early stage, when requirements are first being defined. In many cases this happens. The consequences of a late invitation were clearly shown in the example of the testing and evaluation of the financial system described earlier. With HRED expertise brought into the design cycle late, there was limited opportunity to act on the useful insights gained from the evaluation, which itself was well conducted.

HRED should continue to provide IMPRINT training (beginning and advanced) and demonstrations at conferences of the Human Factors and Ergonomics Society and other organizations that focus on human performance modeling (e.g., Annual Conference on Behavior Representation in Modeling Simulation). HRED can also make available more advanced IMPRINT training. It would be worthwhile to develop courses that focus on how to use the IMPRINT model as part of a larger experimental design approach. As HRED researchers pointed out, modeling is an analysis methodology, and IMPRINT is a tool that supports the analysis. Therefore, greater emphasis should be placed on training users on the appropriate domain and mission analysis techniques as well as the mechanics of developing IMPRINT models.

The current ratio of in-house to customer-funded HSI work—most of the latter is for direct applications work to systems development projects—could be rebalanced if more in-house funds were available to permit more HSI research to improve the state of the art and HSI's tools, such as IMPRINT. The HSI group would also benefit from more personnel, given the number of materiel system evaluations that are requested. This would allow the group to pursue basic scientific work to improve the validity of its tools and to enable the group to increase support for and expansion of IMPRINT tools. Work of this sort is hard to accomplish under customer funding. More in-house resources would allow the HSI effort to advance the behavioral science needed to inform HSI issues (e.g., the impact of automation design on situational awareness and workload, the impact of crew size and structure on situational awareness and workload). This would expand the impact of HSI work within and beyond immediate Army customers and would allow the group to publish more in Tier 1 peer-reviewed proceedings and journals.

## Neuroscience

### Institutional Challenges

The greatest institutional challenge facing the ARL neuroscience program is that of carving out its unique domain within the larger Army neuroscience research establishment. The Army G-1 Office (Personnel) and the Training and Doctrine Command are responsible for training-related neuroscience, and the Army Medical Department manages the Army's more direct biomedical aspects of neuroscience research. Insights and research areas from neuroscience are unlikely to respect these organizational mission boundaries. The neuroscience leadership at ARL has begun to address this issue by engaging in a number of cross-command collaborations that further the overall goals of Army neuroscience while respecting command boundaries. Collaborations of this kind should be strongly encouraged in the years to come as Army neuroscience develops.

Another collaborative issue of this kind involves the relationship between the Army Research Office (ARO) and neuroscience at ARL. ARO has recently developed a clear interest in funding Army-relevant neuroscience. The recent fruitful interactions between ARO and ARL neuroscience projects should be continued and strongly encouraged.

The Cognition and Neuroergonomics CTA, awarded by HRED in 2010, is likely to immensely strengthen the overall neuroscience investment. The HRED group is to be congratulated on the way that it has formulated the CTA. The CTA leverages the areas of expertise at ARL against areas in which expertise is required. Overall, the CTA shows both vision and direction. As the CTA matures it will be essential that the neuroscience group at ARL remain firmly in control of the CTA's many elements and that the CTA-wide group retain the flexibility to address Army goals. The leadership of ARL should encourage the HRED neuroscience group to adjust the elements of the CTA flexibly as the neuroscience group at HRED grows and develops. It is important that the CTA continue to serve the needs of

ARL and not the reverse. Empowering the neuroscience group at HRED to adjust the CTA elements as necessary should yield powerful results.

The neuroscience program shows depth, vision, and organization. It is a model for early-stage development. HRED appears to have an excellent staff on hand, although the continued growth of this staff will be critical for the group. The current staff is, of course, in the early-career stage. This is a strength because it encourages innovation, but maturing the staff and adding senior scientists will be critical as the group matures.

A significant challenge faced by the neuroscience group centers on the issue of growth. The addition of a computational neuroscientist as a senior technologist was imminent at the time of this writing. This will be a very important step for the group and points to the fact that growth in staffing will be critical for maintaining excellence in neuroscience. The group is carefully selecting neuroscientific tools for future use. The group is also developing core competencies in a number of areas (EEG, ICA, fMRI) that will be required in the years ahead. If this small and promising group is to transition to a large, excellent, and high-impact group, it will be essential that ARL leadership continue to support the team with additional hires as well as more space and facilities. Space is already tight for the group, and the current facilities cannot support a group of the projected size. ARL leadership will eventually have to address that point.

### Specific Opportunities in Neuroscience

Following are specific opportunities in neuroscience:

- *Increased focus on multimodal integration:* The HRED neuroscience group should consider the interaction of multimodal information processing with stress, fatigue, and strong emotion. It is obvious that these latter will occur on the battlefield and can have unpredictable effects, leading in some cases to greater focus and in other cases to the disorganization of information processing and cognition. In order for basic discoveries to be translated into useful technologies, such factors must be taken into account. The neuroscience group grasps this problem, at least in theory, and is already beginning to think about useful projects to address stress, fatigue, and strong emotion.
- *Exploring the regulation of brain processes:* The most useful purpose in HRED for beginning a neuroscience program, in contrast to extending an existing HRED psychology program, is ultimately to gain the ability to regulate brain processes involved in sensory integration and cognitive processing and to mitigate confounding factors such as stress, fatigue, and strong emotion. The most important tools for regulating the synaptic mechanisms underlying these functions are pharmacologic. ARL is not currently authorized or equipped to engage in pharmacologic studies; however, a point will come when significant translatable progress will require such inquiry. ARL should begin to consider appropriate collaborations so that organizational boundaries do not inhibit collaborations and thereby limit progress.
- *Exploring neuroplasticity:* The neuroscience group does not currently have a focus on neuroplasticity, but this will be critical in order to illuminate how training experience and battlefield experience alter complex information-processing tasks carried out by soldiers. The limitation of experiments to a small number of trials in the laboratory does not give a full picture of how soldiers will interact with technologies over time.

## Social and Cognitive Network Science

The major laboratory program in social and cognitive network science continues to have significant opportunities to contribute to theory, methodology, and application in this rapidly advancing field. For instance, the CASEL facility provides the capability to conduct laboratory research on distributed multiperson team interactions, making it possible to go well beyond the study of dyads and to address not only communication content, but also the varied properties of the technology that supports such teams. As another example, HRED has the ability to capture networked interaction data from large-scale field exercises involving a significant number of participants over several days. These are merely illustrative examples of the opportunities that the social and cognitive network science program has to contribute to research related to how individual and team activities interact with properties of new technologies (including not only e-mail, but other social networking media) to affect collaborative decision making and performance in measurable ways. However, the scientific output of program research, as reflected by publications in peer-reviewed journals, remains less than desired over time and in comparison with other programs within HRED.

The program faces significant challenges. First, it must define its approach to the social and cognitive network science domain. Two approaches can be seen in the work of other HRED programs. The neuroscience program has made successful use of a top-down approach by first defining key conceptual areas in which the program could gain ground and make significant advances and then describing specific research "thrusts" based on these concepts. A more bottom-up approach is exemplified by the human systems integration program, in which programmatic thrusts and specific projects are heavily driven by client demand. As noted earlier, this is not without its own difficulties, but in both the HSI and neuroscience cases, it is easier to see the shape of the program than it is with the network science work.

There is a noteworthy absence of advancement in articulating the content and structure of the social and cognitive network science domain through an organized and well-defined program of research; there appears to be no strategic plan and logical narrative guiding the program. For instance, the program comprises four major thrusts: multicultural communications, human-team-network interaction, social interaction and simulation, and computational representation. No rationale is provided for the choice of these thrusts: Do they capitalize on existing expertise at ARL? Do they address identified high-priority problem areas? Further, it is not clear how they might be connected into a programmatic research agenda. Indeed, they appear to represent quite different levels of granularity. For example, why is "multicultural communications" not subsumed under "human-team-network interaction"? Similar problems are also evident with subtopics under major thrusts (it appears at times as if an extant project is used to define a thrust, rather than vice versa). Three of the four major thrusts seem to have just a single project each. One would expect a thrust to describe a program of several projects. The existing program seems rather scattershot in nature. Some current projects could be combined and/or restructured around a smaller set of clearly articulated thrust areas. This might result in the phasing out of some projects in order to allow the program's limited resources to be more coherently focused. There is an urgent need to set out the main conceptual or theoretical building blocks for the program. The social and cognitive network science group needs to develop a strategic plan directing the choice of research thrusts and projects that enable the program to contribute to basic science and to warfighter applications.

A second challenge is to address the program's distinctiveness. How can HRED's contributions be differentiated from those made by other programs in this domain, such as those supported by the National Science Foundation, the Office of Naval Research, and the Army Research Office? A third challenge will be to increase the program's productivity in terms of scientific output and outside support. With a sharpened focus on its aims, improved conceptual leadership, and the active involvement of newly hired researchers, such productivity gains would be expected.

## Soldier Performance

As noted above, the Environment for Auditory Research is a world-class auditory facility. However, it remains unclear if there is a utilization plan that will produce world-class results. The panel's concerns remain strikingly similar to those that can be quoted from the previous ARLTAB report:

> Their challenge will be to develop a formalized and coherent set of studies that take full advantage of this outstanding facility, while meeting the unique needs of the Army both to protect soldiers against noise-induced hearing loss and to improve auditory communication and performance. There is a risk that both investigator and laboratory time could be absorbed by short-term practical questions. If time is not set aside for more exploratory basic studies, the scientists may not remain at the cutting edge of the research and it will be difficult to attract the best scientists to the laboratory, thus losing the advantage now provided by such a well-conceived physical facility.[5]

The recruitment of one or more currently productive senior scientists would facilitate the development of a successful program. Even if a senior hire is not possible, a committee of auditory scientists might be recruited to be involved with the EAR in a project-specific manner. These could be off-site collaborators, but the project should have sufficient funding to commit them to efforts beyond those of occasional consultants. Steps of this sort are needed if this excellent facility is to live up to the investment made in its creation.

In the visual domain, there has been a long-standing line of work on the fusion of visible and infrared signals, among other projects. Although there has been some progress over the years, the visual and tactile projects do not seem to have generated the level of output (e.g., in peer-reviewed publications) that might be expected in these areas. In the case of the sensor fusion work in vision, it is not clear whether the project is in adequate contact with the very substantial work on this topic that occurs elsewhere in DoD and other domains (e.g., medical imaging).

A well-thought-out research plan aimed at taking maximum advantage of the unique capabilities of the omnidirectional treadmill facility should be developed. As of this writing, such plans were not in evidence, and they should be developed and presented for review as soon as possible. Additional planning challenges will be to demonstrate how research work planned for the new ODT facility will be complemented by the newly upgraded mobility and portability test course (at the Known Distance Range at Aberdeen Proving Ground) in an integrated research and applications program.

The HRED field unit at Fort Sam Houston has been engaged in studies of early identification of the presence of mild forms of traumatic brain injury and perhaps accompanying post-traumatic stress disorder. This is a topical and important problem. However, as noted earlier, in order to be a viable research project, this would have to become a more substantial research program. ARL needs to determine if there is a viable role for the Fort Sam Houston field office in the study of such medical research issues or whether it needs to expend its energies elsewhere. The group was also asked to evaluate a neurocognitive training intervention technology (interactive metronome and videogame playing) on pass/failure rates in the course. The basis for selection of the interactive metronome appears weak (there was little evidence of its effectiveness). If this project were to progress, the metronome should, at a minimum, be compared with some alternative.

[5]Ibid., p. 34.

## OVERALL TECHNICAL QUALITY OF THE WORK

To summarize the overall technical quality of work in HRED, it is useful to consider four topics: broad scientific vision, technical resources, quality of work at the individual project level, and scientific output.

### Vision

Clear and appropriate vision is central to the future success of HRED's scientific mission. There is no doubt that important topics are under study in each of the five broad areas reviewed above: human robot interaction, human system integration, neuroscience, social and cognitive network science, and soldier performance. The neuroscience group articulates a clear vision: It wants to use modern neuroscience to enhance soldier-system performance. The group recognizes this as a very broad mandate, and so it has focused on specific projects in which it can make a unique contribution. Therefore, it is putting considerable effort into taking sensitive methods from the laboratory and getting them to work under less-forgiving conditions—that is, conditions experienced by the Army in the field. This leads to an interest in muscle artifacts in EEG, wearable devices, and single-trial methods, for example.

The social and cognitive network science area is also both broad and important. Here, however, it is less clear that there is a vision of HRED's role. There are multiple projects on many interesting topics, but it was harder to discern the thrust of the overall effort—a strategic plan for an organized, focused program is needed.

In the area of human systems integration, the vision is more mature and customer-driven than in an emerging area like neuroscience. This is an observation, not a criticism. The group has a primary focus on modeling how complex systems will function once deployed. The HSI group might consider a long-term strategic planning exercise to identify where it might go next, but for the present, it has a clear role and is setting about fulfilling it to the extent that resources permit.

The human robot interaction group would be aided by a clearer vision of where it sits in the broader field both inside and outside the Army. Within the Army, there may be more opportunities for collaboration and a sharing of resources. More contact with the broader academic community might help to identify the areas in which the HRI group could make its unique mark.

The most creative energies of the soldier performance group seem to have been focused on the development of new facilities such as the EAR. Like HSI, now that those facilities are in place, the group would benefit from a planning exercise to envision what distinctive HRED work can be done with these tools.

### Resources

The development of the EAR, the omnidirectional treadmill, and other facilities shows HRED's ability to muster the funding and the skills to create world-class facilities. Ongoing efforts of a similar variety will be needed in other areas. The neuroscience group in particular is likely to need substantial investments in equipment and facilities if it is to live up to its potential. This is simply a recognition that neuroscience is a growing program. In other cases, the resources that could be developed are human resources. Many parts of HRED could readily absorb new hires. The HSI IMPRINT effort is one example.

## Research Quality

As a broad generalization, the HRED work is being done at a high level of competence. As noted above, there might be questions about why a specific study was worth doing, but as a general rule the mechanical details of research are well done. Questions have been raised in the area of statistical analysis and interpretation. In some cases, the analysis did not seem to be the correct analysis. In other cases, the distinction between statistical significance and scientific or practical significance was lost. These issues tend to arise in presentations by junior investigators and point to the ongoing need for mentorship, "brown-bag presentations" of research to internal groups, and the vetting of research by the processes of peer review provided by participation in national and international meetings and the submission of work to rigorous, peer-reviewed journals.

## Scientific Output

In terms of its scientific output, HRED has increased its emphasis on publishing work in the open, peer-reviewed literature, but for a group the size of HRED, that output remains modest. The bulk of publications are book chapters, conference proceedings, and technical reports. Although useful, this output is not the same as publication in journals that are routinely indexed in databases (e.g., PubMed) and whose citations would be tracked by ISI Web of Knowledge or other citation indexes. Publication in these outlets is, in a sense, the currency of academic science and the most direct way for work in one laboratory to influence work in other laboratories. Promotion cases in university departments are heavily influenced by the quality and quantity of such publications. The current output at HRED would not support academic promotion in many cases.

The Human Research and Engineering Directorate should give stronger consideration to the publication of path-breaking HRED research in high-impact scientific journals.

# 4

# Sensors and Electron Devices Directorate

## INTRODUCTION

The Panel on Sensors and Electronic Devices is charged to review the research activity of the Sensors and Electron Devices Directorate (SEDD). The panel met at the Army Research Laboratory (ARL) facility in Adelphi, Maryland, on July 13-16, 2009, and June 2-4, 2010. During those two meetings, the panel reviewed research portfolios in all four SEDD divisions: Electro-Optics and Photonics, Energy and Power Generation, Radio Frequency and Electronics, and Signal and Image Processing.

The review focused on both internal research projects and collaborative activities. SEDD is currently participating in Collaborative Technology Alliances (CTAs) in Robotics, Network Sciences, Cognition and Neuroergonomics, and Micro-Autonomous Systems and Technology (MAST). It also has several research centers and institutes focused on flexible displays, fuel processing, biotechnology, nanoscience, and microelectronics manufacturing. SEDD also participates in the International Technology Alliance (ITA) program.

Table A.1 in Appendix A characterizes the staffing profile for SEDD.

## CHANGES SINCE THE PREVIOUS REVIEW

Although the number of scientists and engineers at ARL has changed little since the previous review by the Army Research Laboratory Technical Assessment Board (ARLTAB), the fraction of technical staff that have earned doctorate degrees is trending up and is now approaching 50 percent. ARL management has adopted a well-conceived planning process that links institutional goals to strategic hiring goals. Within SEDD, strategic competencies among the staff are linked to addressing current and anticipated Army needs. The excitement and energy of the scientific staff are impressive. The directorate has clearly improved its ability to attract top-notch early-career scientists. Particularly notable are the doubling of the number of postdoctoral fellows, from 12 to 24 since the previous review, and the staff turnover rate of around 10 percent per year.

There has been a similar improvement in the output of technical publications and patent disclosures. The average number of refereed technical publications in the 2 years since ARLTAB's previous report[1] has increased more than 29 percent. After a small drop in FY 2009, the number of new patent applications increased by 30 percent in FY 2010. In addition to publications, SEDD staff members have won a significant number of research and service awards both within the governmental service community and outside the laboratory.

Given that sensors and electronic device technology are constantly evolving, one of the expectations of SEDD is that it continuously update its research portfolio to keep pace with these changes. SEDD has addressed this expectation in the current, 2009-2010 reporting period by increasing its in-house research efforts in several areas, such as wide bandgap materials, image processing, flexible displays, and battery chemistries, while moving on from unattended ground sensors and sensor integration and transitioning silicon carbide (SiC) device research from in-house to external projects. More significant is that these changes are guided by a clearly stated long-term vision for each of the major SEDD mission areas. For example, the extreme energy and power vision describes an objective of providing the individual soldier with access to two to three augmented energy sources on the mesoscale and microscale. The heterogeneous electronics vision foresees intelligent systems built from multiple technologies integrated into clothing, vehicle surfaces, and other structures in the warfighter's environment.

As research evolves, so must the facilities and equipment used to conduct that research. In the current reporting period, SEDD has invested $12.5 million in new equipment and laboratories. Most of these funds were spent on new and upgraded instrumentation, and investments were spread among all SEDD divisions.

Among the "crown jewels" of SEDD facilities are its extensive semiconductor fabrication lines. This facility has developed into an extraordinary research support tool capable of producing a diverse set of advanced semiconductor devices, all of which are critical to the ARL SEDD mission. However, the facility is in need of a major review even though it has been continuously upgraded since 2002. Much of the processing and support equipment is nearing the end of its useful life span. The maintenance status and the impact of the introduction of new process procedures need to be reviewed, and the SEDD management needs an independent, objective look at all of these issues and must be prepared to make significant investment in the near future to keep this capability at the cutting edge.

## ACCOMPLISHMENTS AND ADVANCEMENTS

### Energy and Power Generation Division

There has been a significant and encouraging change in vision in the Energy and Power Generation Division during this reporting period, reflecting the evolution of the energy and power field in general. There has also been a good deal of progress in addressing several challenging problems in the field. The division is organized into three branches: Electro Chemistry, Power Components, and Power Conditioning. Following are highlights of current research efforts in the branches.

The effort in reforming Jet Propellant 8 fuel (JP-8) to power (hydrogen or solid oxide) fuel cells is expected to net a total fuel-to-electrical efficiency of approximately 30 percent (about twice that of

[1]National Research Council. 2009. *2007-2008 Assessment of the Army Research Laboratory.* Washington, D.C.: The National Academies Press.

conventional power generators). SEDD has taken an interesting approach to this problem based on a two-stage cleanup of fuel (removal of sulfur) and onboard reforming.

Battery research continues to be a strong area, and as a result the weight and effectiveness of the soldier's battery load continues to improve. SEDD is pursuing several investigations, ranging from lithium-polycarbon fluoride-oxygen ($Li/CF_x-O_2$) hybrid batteries, a promising commercially available chemistry, to lithium air batteries, an exceptionally difficult set of challenges. Even the scaling of existing technologies into the soldier power domain has proven to be a big challenge. SEDD has had significant success during the past 2 years in addressing many of these challenges in soldier power.

In the area of SiC switching devices, SEDD has made and likely will continue to make important contributions to high-temperature power electronic systems at every level of technology, including capacitors, inductors, thermal management technology, circuit devices, and materials. Over the years SEDD has played a key role in the development of high-power/high-temperature electronics. The program is a good example of properly placed resources and persistence leading toward success.

The air core inductors project has achieved impressive performance, with inductance values and Q values that are quite high for the technology. The next step is to integrate this technology into a micro power converter. To that end, an approach based on nanodeposition by capillary action for on-chip inductors and capacitors has been proposed. In early stages, this technique has a potential payoff that is not limited to building energy storage components.

## Radio Frequency and Electronics Division

The Radio Frequency and Electronics Division is focused on the development of next-generation electronic devices and sensors for Army systems operating in complex environments. Research in this division is organized into four branches: Micro- and Nano-Electronics Materials and Devices, Electronics Technology, Antennas and RF Technology Integration, and RF Signal Processing and Modeling.

The Micro-Autonomous Systems and Technology CTA is the centerpiece of the microrobotics research efforts in this division. The work is extremely impressive and demonstrates multiple capabilities to develop and/or integrate the very innovative advanced technologies required. Highlights of this system are these: (1) integration of the 250 GHz miniature 400 m range radar (developed by the University of Michigan), (2) the thin-film piezoMEMS (microelectromechanical system) bio-inspired wing, (3) the high-performance air-core MEMS inductors and transformers, (4) a novel nanoparticle delivery method for capacitor fabrication, and (5) nano-Rectanna for efficient energy harvesting. The MAST program is an excellent example of the role that SEDD should play in developing Army-centric technologies. It also highlights the fact that the nature of power and weight requirements is a moving target and requires constant collaboration.

Some of the most innovative research in SEDD is the piezoMEMS actuators for the microrobotics effort. It has certainly advanced the state of microstructures. Two important features were incorporated here: first, the use of the piezoMEMS processing capability to create the low-power micromotion; second, the construction of a two-dimensional (up-down combined with rotation) flapping wing that emulates biological capability. This work also supports the MAST program. Until this millimeter-scale mobility could be demonstrated, the "air" portion of the MAST program was nothing more than creative viewgraph engineering. In that sense, this effort has validated the MAST vision.

Another piezoMEMS project is investigating phase shifters as an element in the compact radar project. The work is on electronically scanned arrays, and the phase shifters have achieved 5 to 10 V activation, as compared with the 30 to 100 V achieved for others.

Both of these piezoMEMS projects emphasize the importance of the SEDD Semiconductor Fabrication Facility. The fabrication of piezoMEMS devices utilizes a unique process. It would very difficult, if not impossible, for SEDD to have this done at an outside fabrication facility, which could not customize its process, and whose processing delays would hamper the research substantially.

The radio-frequency prognostics and diagnostics for condition-based maintenance project has put together the correct set of comprehensive tools to solve an extremely important problem for the Army. The prognosis approach was particularly impressive, because it combined an intelligent choice of sensors with a layered set of complex algorithms for failure prediction.

The broadband digital waveform synthesis project has successfully achieved effective compensation for cross-talk errors generated when using multi-amplitude, multiphase modulation techniques such as quadrature amplitude modulation (QAM). The technique has been shown to compensate for transmitter nonlinearities for a 32-QAM system. The investigators predict that this method can increase the transmitter dynamic range by 20 dB.

In the Antennas and RF Technology Integration Branch, the compact millimeter-wave radar and advanced imaging project exploits a very clever idea of using stacked single antennas to get azimuth coverage quickly while minimizing complexity. It has also adopted a very interesting computational imaging system that is a hybrid of optical and radar approaches for a stepped-frequency, holographic radar imager. This combination has the potential to be a very interesting testbed that can link experimental data with new processing algorithms.

Highlights in the RF Signal Processing and Modeling Branch include the SIRE (Synchronous Impulse Reconstruction) Ultra Wideband Radar Program, which represents an excellent example of the SEDD research with the potential for a significant impact on the capabilities of a warfighter. It has multiple potential uses: (1) the detection of concealed obstacles behind foliage, (2) surface and buried mine detection for autonomously and nonautonomously operated vehicles, and (3) through-the-wall detection in an urban environment. The system is capable of many novel techniques, such as forward-looking synthetic aperture radar operation for determination of the height of obstacles, through-the-wall detection of moving people using noncoherent back projection, and change detection. It uses a very short pulse (~300 picoseconds [ps]), yet it employs a low-cost analog-to-digital converter. Its relatively low maximum frequency of operation of S band permits seeing through foliage and through building walls. Several challenges remain—in particular relating to real-time processing capabilities—but this is a high-payoff project with significant progress in the current review period.

Research in SEDD on the III-nitrides continues to be of the highest quality. The project carrying out this work showcases the expertise, exceptional instrumentation, and technical capabilities of SEDD, and it demonstrates the pivotal role that SEDD plays in the III-nitride community, serving as an impartial, highly respected evaluator that can knowledgeably assess materials from different laboratories, providing conclusions and comparisons that can influence the field to make improvements in materials. These insights also inform the research program internal to SEDD. Internal projects show great understanding of the important applications for the Army, and in general they also demonstrate sophistication in the understanding of materials and electronic structures, how best to engineer device structures, and how to characterize their behavior. SEDD has addressed important issues in high-efficiency deep ultraviolet devices and has made advances in the very critical droop in InGaN devices.

High-performance infrared sensors are an important application for the Army, and HgCdTe is a critical material to enable those sensors. Driven by issues of cost and performance for large-area detector arrays, SEDD has taken a leadership role in developing a composite substrate technology based on Si, carrying out fundamental studies in growth and processing to reduce defects arising from the lattice-mismatched growth of HgCdTe on those substrates, and establishing the correlation between defects and device performance. SEDD researchers have amplified their efforts in this area by coordinating a network of small companies, larger companies, and universities to address comprehensively the issues of materials characterization, processing, device architecture, and array fabrication and characterization.

The SEDD project on dilute nitrides as an alternative, low-cost approach to achieving long-wavelength infrared (LWIR) detectors has incorporated some extremely clever and interesting ideas: leveraging the use of nuclear resonance analysis (used to study gun barrel erosion) to sensitively map out N concentrations and locations, and using transmutation doping to achieve p-type doping in the material. The ability to construct an LWIR detector from III-V materials is extremely important for the Army. This work is impressive because a newer material, InAsSbN, has been selected, and a technique for growing it in a lattice-matched condition has been demonstrated.

The SEDD effort on polarization properties of nitride semiconductors has achieved a key breakthrough in the fabrication of a GaN single-heterostructure light-emitting diode (LED) with the p-side down. By placing the p doped side on the substrate, a potential barrier is introduced that limits the electron overshoot into the p-GaN layer. The results show a factor-of-five reduction in efficiency droop over conventional GaN LEDs at high current density (>100 $A/cm^2$). This new structure also offers a real chance to make a high-efficiency solid-state ultraviolet laser.

Working in coordination with the Flexible Display Center in Arizona, SEDD has become the leader in flexible display technology and is stimulating the industry. The Flexible Display Center appears to be bearing fruit, and industry is participating and contributing technology.

SEDD efforts in biotechnology have established or enhanced ARL expertise in this area of importance to the Army. Investigators appear to have an excellent understanding of the opportunities and limitations of the science, the instrumentation, and the Army-related applications. Two efforts of note are the Affinity Reagent Isolation for Pathogen Detection and the Cell-Based Sensing projects._

Signal processing is fundamentally a systems technology in which algorithms are developed to solve key systems needs. Superb results are achieved when those developing such algorithms have the advantage of a deep understanding of the problem. High-quality work benefits enormously from direct exposure to the real problem and real data. The RF Signal Processing and Modeling Branch has a track record of outstanding work in this area, with its deep involvement with technology now in use in Iraq and Afghanistan.

A good example of a high-value outcome from this branch is the Acoustic Signal Localization and Classification project. The goal is the use of acoustic sensors to detect an explosion or firing location with sufficient accuracy to cue a sensor or response. Unfortunately, spatial- and time-varying temperature and wind gradients both change the direction of arrival of the signal and, through multipath, distort it. This distortion puts limits on how such sensors can be used. Getting more value from acoustic sensors by removing this distortion is a very hard problem that is now being examined at ARL. There has been a great deal of work over many years aimed at modeling these effects with sufficient accuracy to permit compensating for the effects by processing. With a great deal of expertise, SEDD continues to develop a model to help address this problem.

The current focus of SEDD efforts in sensor and information fusion for coalition networks is authentication and sensor-network-access permissions, which are of great practical importance for deploying among coalition forces a system used in a hostile environment. This work is set against a backdrop of more general fusion processing that must effectively integrate information from sensors with very different types of information in terms of kind, quality, and timeliness. The project team has properly identified the need to address fusion in the context of real data from specific sensors. Such a system is very likely to be of greater value than sensor information that is fused at a tactical level only and then fed forward.

One of the image-processing efforts associated with the SIRE radar is the Through-the-Wall Detection of Moving Personnel project. It is focused on detecting through walls the number and location of individuals within a structure. The current effort has a good processing architecture, with the individual components well executed. The processing now is largely addressing the problem of finding the interesting signal associated with moving personnel amid other returns. The current results are separated from the background by exploiting the regular movement of simulated persons. This is a good first step, with ongoing efforts focused on the kind of movement that can be expected of persons in realistic scenarios.

## OPPORTUNITIES AND CHALLENGES

SEDD researchers have demonstrated significant cleverness in solving problems faced by the Army. Cleverness of approach can be as important a metric as standard academic measures (e.g., journal publication) for judging quality of science. This section lists a number of specific opportunities for investigators within SEDD and outlines some of the particular challenges being addressed by SEDD staff.

- Micropower is an especially promising area that, with the application of adequate resources, could produce outstanding results that could be transitioned ultimately to fieldable technologies. This area is particularly important because of its impact on many of the projects that fall under SEDD's interest areas.
- The SiC area represents a success for SEDD. This has been a long-standing area of investment owing due to the Army's need for high-power switching components. This effort is unique and very appropriate to ARL's niche. Partly as a result of this investment, SiC metal-oxide semiconductor devices are now being commercially offered by two vendors, Cree and General Electric. SEDD's role is now evolving but should not be eliminated. The new mission is to take part in the reliability evaluation and the setting of standards for the industry. As SiC is transitioning to a more commercial technology, SEDD can explore the possibilities of the III-nitrides as switches. Development of the III-nitride switching devices is a very long term materials-based effort. As is the case with SiC, few other organizations can be patient enough to provide the long-term support to solve the materials issues. SEDD is in a unique place in this arena.
- Fuel cell research within SEDD is making progress. The researchers are active in the community and are publishing. JP-8 reforming is an excellent strategic area that should be developed by SEDD. There is a clear need from the Department of Defense for this technology and no strong commercial driver for it. This is an area in which SEDD could make significant impact. That being said, it is also a long and difficult road that will require sustained and disciplined work.
- Strategic investments in materials technologies can have broad applicability throughout the divisions in SEDD. For example, the wide bandgap materials influence the Radio Frequency and Electronics Division's work in GaN power electronics, the Electro-Optics and Photonics Division's work in deep ultraviolet optoelectronics, and the Energy and Power Generation Division's work in SiC electronics. Within a given division, there may be a range of technology choices that can be explored. Where there are common applications that can be met by competitive technologies (e.g., power switching through wide bandgap electronic devices: SiC versus GaN), it is important to carry out periodic internal benchmarking and comparison to avoid redundant efforts and to make the best use of limited resources.
- The staff in the life sciences at ARL have developed a more sophisticated understanding of Army needs, are immersed in meaningful collaborations with organizations both intramural (other ARL directorates) and extramural (e.g., the Institute for Collaborative Biotechnologies), are making

reasonable progress establishing life science experimental capabilities, and are starting to develop focus areas. That said, ARL and SEDD management have some significant and difficult focus decisions to make in the next few years. More application-driven advice from senior life scientists (rare people to find outside of industry) is needed to help management with the decisions as well as the later stages of the current projects.

- In signal processing there is a "clear and present overload" of data coming from the imaging sensors that are being used with great success throughout hostile regions. The huge data sets generated exceed the capacity of tactical communications links. As a result, data that must be analyzed often take too long to get into the right hands and consequently do not achieve the impact that they should. A very high payoff can result from technical work in the area of automated tactical alerts designed to flag and prioritize data that should be urgently transmitted over the limited communications links available. Such an effort should be explicitly constrained to run on hardware with limited power and weight. Through its processing expertise and classified programs, ARL is in a unique position to make such a contribution.
- The SEDD Semiconductor Fabrication Facility has again proven to be a success story for enhancing research at ARL. As discussed in the previous ARLTAB review of SEDD activities, the Semiconductor Fabrication Facility is a magnet for early-career researchers and has aided in their recruiting. In addition, it has fostered collaborative research with other organizations, acting as a technical force multiplier. The technical difficulties in managing a semiconductor facility that supports so many types of processing are greatly increased over those in a facility that supports only one type of processing—for example, complementary metal-oxide semiconductor or GaAs. Issues abound over the use of common equipment with potential cross-contamination and the maintenance of tight process control with the different process lines. In this regard, only a few top-ranked universities have achieved a high performance level, but SEDD has also mastered it. ARL has done well to continue its investment in the maintenance and modernization of this facility and must be prepared for the significant investments necessary to keep this facility equipped with state-of-the-art technology.

## OVERALL TECHNICAL QUALITY OF THE WORK

The scientific quality of the research at SEDD is of comparable technical quality to that executed in leading federal, university, and/or industrial laboratories both nationally and internationally. The balance between work on projects with immediate applications to the war zone, such as the detection of improvised explosive devices, versus basic research work, such as that on the cold atoms, is very good. There is also evident an impressive level of the involvement of other agencies and civilian industry in the ARL projects both as collaborators and as customers.

Measured by refereed publications and citations, SEDD is doing very well. According to the data supplied to the panel for the 18-month period from January 2009 to June 2010, SEDD staff published 136 refereed journal papers and presented 522 papers at conferences and symposia. Of the presentations, several are invited and international—for example, by the 50th Battery Symposium in Japan. Several papers on fuel cells and batteries were presented at the Electrochemical Society meeting in 2008 in Honolulu, which is impressive. Based on the data provided, the average publication rate for individual SEDD staff is comparable to the averages of university-based researchers and slightly better than those of most industrial laboratories. The publications are in good-quality journals and at top-tier conferences. In FY 2009, 20 patents were awarded to SEDD researchers, and 27 new applications were filed. This is a track record of a solid research organization.

There are several crown jewel projects in which SEDD researchers are leading the field. Most notable is the work in quantum detectors and III-nitride materials for sources and detectors. SEDD's leadership in this field stems not just from its top-notch scientific staff but also from the world-class fabrication facilities that it maintains. Another area of SEDD leadership is in acoustic processing and electromagnetic field sensing. SEDD researchers in this area can point to immediate impacts on the battlefield: several systems from this group have been deployed in recent years. Semiconductor power switching and conditioning devices are also an area of leadership. This results from a combination of quality staff, excellent facilities, and a direct application to Army requirements. Although its participation in the Flexible Display Center is not an internal program, it is important to note the role that SEDD plays in the center. Flexible display technology promises potentially extensive consumer and military applications. However, in some specifications, devices for these two markets may not coincide. The participation of SEDD in this center, generally to assist in the advancement of the technology, but additionally to see that military needs are met, shows significant foresight by ARL and SEDD management.

In general, the quality, enthusiasm, and morale of SEDD staff are excellent. Such indicators of the scientific culture of an organization can be as important as quantitative measures such as papers, citations, and patents for assessing the quality of the science. Interactions among enthusiastic colleagues lie at the forefront of scientific advances, because often ideas are sparked during both formal and informal conversations with colleagues. SEDD is clearly fertile ground for such interactions.

# 5

# Survivability and Lethality Analysis Directorate

## INTRODUCTION

The Survivability and Lethality Analysis Directorate (SLAD) was reviewed by the Panel on Survivability and Lethality Analysis of the Army Research Laboratory Technical Assessment Board (ARLTAB) during June 22-25, 2009, at White Sands Missile Range in New Mexico and during July 25-28, 2010, at Aberdeen Proving Ground, Maryland.

SLAD's mission is to provide expert assessment and evaluation support with respect to the survivability, lethality, and vulnerability (SLV) of Army equipment and soldier systems in the context of full-spectrum battlefield environments, with a goal of ensuring that soldiers and systems can survive and function reliably to be lethal to enemy forces. SLAD performs this mission through the development and application of well-founded testing and evaluation (T&E) methodologies and facilities; deterministic and probabilistic tools comprising physically motivated, empirically based damage-assessment models; experimentation; simulation; and theoretical analysis, all integrated with a solid understanding of battlefield functional requirements. The SLV assessments are performed throughout the entire life cycle of Army systems, from development through acquisition, deployment, and operation. SLAD's mission supports Army Headquarters, program executive officers, program managers, system developers, contractors, and other defense-oriented laboratories.

SLAD is composed of two divisions: the Information and Electronic Protection Division (IEPD) and the Ballistics and Nuclear, Biological, Chemical Division (BND). The SLAD portfolio consists of many small T&E programs directly related to the assessment of specific Army components, with several larger programs aimed at developing tools necessary to enhance T&E efforts and to broaden the scope of the SLAD contribution to Army system life-cycle assessment. In each 2-year review cycle, the panel is exposed to about 90 percent of the SLAD programs at some level, but to less than 20 percent of the portfolio at a level sufficient to assess in depth the technical quality of the work. The panel focused on those programs with the strongest continuity of effort, with the addition of a crosscut of new and mature programs to provide the context of the full spectrum of work performed within SLAD.

Table A.1 in Appendix A characterizes the staffing profile for SLAD.

## CHANGES SINCE THE PREVIOUS REVIEW

The SLAD portfolio and evaluation structure are based strongly in the directorate's long history of critically important and successful ballistics-based vulnerability assessment, which has supported the Army testing and evaluation activities. SLAD has continued to broaden its program base to include the assessment of the vulnerability of communications, networks, and information processing on the battlefield.

SLAD has taken the Mission and Means Framework (MMF) for analysis and incorporated it into a larger analysis methodology called Mission-Based Test and Evaluation (MBT&E). SLAD legacy tools only evaluate performance but not the effect on mission. The objective of SLAD's MBT&E methodology development is to add the capability of assessing how the loss of performance affects mission requirements. MMF, a methodology described in the previous ARLTAB review,[1] defines the "mission capability requirements" from the top down, starting with strategic national, to strategic theater, to operational, to tactical, to task. Thus, all of the tasks required to perform a specific mission are defined. "Capability" is defined from the ground up, starting with deployed forces, up through the subsystem, to the platform capability. Top down, a set of mission-required tasks is defined; bottom up, a set of mission capabilities is defined. The MBT&E analyses then match requirements with capabilities and the effects of threats on both, resulting in a "mission performance degradation assessment." SLAD now has, conceptually, the capability to tie together all capability and performance metric assessment groups and/or tools into a mission framework, including those of the Human Research and Engineering Directorate (HRED); the Tank Automotive Research, Development and Engineering Center (TARDEC); and survivability, lethality, and vulnerability assessment (SLVA). MBT&E is intended to provide the linkage between any functionality or degradation and mission capability. Three pilot programs have been identified for the application of this new methodology. One of the pilot programs will utilize S4 software (System of Systems Survivability Simulation) and MUVES 3 (Modular UNIX-based Vulnerability Estimation Suite) as tools within the MBT&E framework.

It is notable that after trying the MBT&E process, the Director of the Army Evaluation Center (AEC) decided that it would be used for all AEC projects. The systems capabilities analytic process demonstrated meaningful results that SLAD customers want. Using it, they can directly correlate testing and modeling results to mission task success. According to SLAD, the directorate is the only organization actively developing a process to link quantitatively from a system's capabilities to a system's components. This is an excellent example of an opportunity for the expansion of a successful methodology to application with other activities.

SLAD has now imposed a more formal structure for program management. The directorate has an internal steering committee (including both SLAD division chiefs) that provides management oversight of the system-of-systems analysis (SoSA) program manager and subordinate SoSA operating teams. In addition, the SLAD Director has stood up a project management office within his staff as a resource on project management processes, practices, and procedures for all programs within SLAD, including SoSA. SoSA and MUVES 3 are the two places where SLAD has been the most successful with

[1]National Research Council. 2009. *2007-2008 Assessment of the Army Research Laboratory.* Washington, D.C.: The National Academies Press.

implementing its project management strategies, but these projects were also the ones most in need of such support. SLAD has also instituted a matrix structure that appears to be a creative way to balance the culture of innovation and prototype development with program support. This approach should be promoted, but a critical concern is whether the leaders who are equivalent to program and/or project managers have the requisite control over resources necessary to be responsive to sponsors' needs, or whether they are simply internal coordinators.

Perhaps the largest change that occurred during this review cycle was the cancellation of the Army's Future Combat Systems (FCS) Program. Much of the focus of SLAD's analytical tool development had been on developing the capability to assess systems being considered under the umbrella of FCS. The SLV assessment tool methodology focus has now shifted to assessing the Ground Combat Vehicle (GCV) Program. It is not yet clear how the change in focus will affect the SLAD tool development process.

## ACCOMPLISHMENTS AND ADVANCEMENTS

SLAD management is aware of the importance of hiring creative, energetic, and innovative professionals, as well as competent and enthusiastic early-career engineers and interns. Management also recognizes the value of professional development and provides several methods for this: pursuit of advanced degrees, certifications, personal leadership opportunities, developmental assignments, conferences, and collaborations. More emphasis should be placed on continuing education, to enhance the knowledge and experience base in the principles of basic research and to broaden the scope of collaboration outside the Army Research Laboratory (ARL).

### Response on Improvised Explosive Devices

In wartime, rapid response to soldier-in-the-field challenges is imperative. SLAD personnel have provided exemplary service to their country in this time of war with their dedication and "can-do" attitude. This highly motivated, mission-aligned, enthusiastic group of engineers and technicians has made significant contributions to the Army and the Department of Defense (DoD) through creative problem solving and solid engineering know-how. An excellent example of this effectiveness is the program in radio-frequency (RF) countermeasures. This program is very impressive. This group has provided effective response to Army needs and support of Army personnel, demonstrating a high-energy, creative approach to solving problems quickly while maintaining cost-consciousness. This support work for the Joint Improvised Explosive Device Defeat Organization (JIEDDO) is commendable and an impressive help to Army field personnel. The modular approach used in this program ensures extensibility of the methodology to enable quick turnaround on future problems. This program also shows a good use of existing software for analysis.

### Target Interaction Lethality/Vulnerability Program

The Target Interaction Lethality/Vulnerability (TILV) Program is an excellent example of an SLAD strategic program aimed at improving SLAD's vulnerability analysis capabilities. A typical TILV project is 3 to 4 years in duration and is designed to address a significant methodology shortfall. Some examples of recent projects include the work on underbody blast effects and the work on ballistic impacts on helmets.

The development of underbody blast methodology is well thought out and is commendable for filling a critical need in this area. The methodology combines appropriate physics and necessary codes to assess damage to vehicles. There is a good understanding of the limitations of the various elements that are interconnected to form the overall methodology. This is a notable example of research that could have an impact on the next generation of vehicles. The work is being presented at appropriate conferences and would benefit from peer review for publication in archival journals.

The work on ballistic impacts on helmets is a good example of solid engineering using well-established principles to improve test standards. This program provides an excellent opportunity to collaborate with outside experts to define and conduct further research efforts in this area.

TILV projects demonstrate SLAD's collaboration efforts with the Army Research Laboratory's Weapons and Materials Research Directorate as well as with the U.S. Air Force Research Laboratory (AFRL). There was also commendable collaboration in international data-collection efforts using facilities such as the test ranges at Aberdeen Proving Ground, Maryland; facilities at Adelphi, Maryland; and Eglin Air Force Base, Florida; as well as at ARL's computational facilities. Past TILV projects have contributed to the development of the end-to-end active protection system (APS) model and to improvements in the models used to predict the blast field created by munition detonations.

The TILV Program is a very good example of effective project management. Each project has clearly defined objectives and is a customer-driven, short-term project to address perceived, or customer-defined, issues (modeling and testing shortfalls). Each project has an "end" metric that includes a time limit. These termination time limits avoid any pursuit of activities that are beyond what is reasonable and practical.

## Software Development

Prior ARLTAB assessment reports suggested that SLAD management needs to achieve a better balance between tasks that are more beneficially performed in-house and those that are best outsourced. There were several programs in the current review cycle in which commercial-off-the-shelf (COTS) software was effectively utilized to enhance SLAD capability, demonstrating an admirable change to the in-house paradigm. The Optical Augmentation Micro/Macro Modeling Program is one example of the effective use of COTS technology and of intelligent outsourcing. By hiring an outside vendor to integrate existing COTS tools, SLAD personnel and budget were freed up for what they are uniquely qualified to do: that is, to understand the military requirement, locate the tools and methods to address it, and apply the software for SLAD-specific uses. The Virtual Shot Line (VSL) Program approach provided another example of an application of commercial computer-aided design (CAD) tools and formats: these were used in the VSL Program for the successful generation of a program that works in real time to evaluate and identify which components of a vehicle are affected by a projectile or fragment following a given shot line and what effect the shot will have on vehicle subsystems and system performance. The program exploits work previously done in ray tracing for radio propagation. The use of standard geometry formats and commercial CAD tools reduced the programming effort by a large factor and also reduced computation time. SLAD staff and its customers are equally enthusiastic about this new capability.

The VSL Program demonstrated many programmatic aspects found missing in previous program reviews, from both a technical and a managerial perspective. First, on a technical level, the use of graphics-processing-unit programming technology makes supercomputer performance possible on a desktop for certain highly parallel tasks. Architecture decisions for SLAD's next-generation ballistic vulnerability/lethality model, MUVES 3, should be reviewed to take advantage of this new capability if possible. The VSL Program has admirably demonstrated its ability to display interactions between subsystems and the system that they support and to identify critical nodes whose failure can have catastrophic impact on the system if they are not better protected. This approach is applicable far beyond the fighting vehicle, and other systems can benefit from future application. The way in which the VSL project was executed—sending an SLAD analyst on a development assignment with a major external research organization—represents a significant departure from SLAD's traditional way of doing business, as well as a possible new paradigm for how SLAD can use external contacts and collaborations as a force-multiplier for its limited resources. SLAD management's seizing of this opportunity to commit to this experiment is commendable, and new and even more exciting moves in this direction are to be expected in the future. Internal SLAD reviews for the funding of future projects require a serious consideration of opportunities for in-depth external collaboration, and periodic reviews should be made to ensure that those opportunities have been exploited.

### Laboratory Facilities

The laboratory tours during this review period clearly demonstrated the high level of enthusiasm of the personnel who have access to the numerous SLAD state-of-the-art facilities. Many problems critical to the SLAD mission are being addressed, including that of protective armor for personnel. The collection of programs on weapons effects on personnel is commendable and should serve as an excellent database for comparison and evaluation. The cooperation with various federal agencies and industry is exemplary. The gel block methodology that is being developed to study the effectiveness of body armor is a promising direction that could lead to fundamental insights for future designs. The helmet testing utilizes advanced measurement methods and is currently used as a screening tool.

The recently established Electro Magnetic Vulnerability Assessment Facility (EMVAF) is a state-of-the-art facility with the goal of evaluating and investigating antenna performance, vehicle effects (jamming and communication), and multipath effects. The facility is impressive, well designed and managed, and well staffed by dedicated and energetic personnel. The management should be commended for conceiving, designing, and developing this facility, which serves many critical missions and needs of the Army. SLAD has increased its ability to maintain a leading edge for this sort of analysis.

## OPPORTUNITIES AND CHALLENGES

The SLAD organization appears to be evolving from what was once primarily a testing and evaluation service organization to an organization that now also includes methods and process development functions for analysis and evaluation. This mission drift seems quite appropriate, given the nature of the tasks and uniqueness of the products and systems being analyzed. The development of the underbody blast methodology initiative is a good example of where it makes sense for SLAD to be active in research to support the vulnerability function. However, in order for SLAD to transition to this extended mission, the focus of the organization needs to include research as part of that mission.

### Communications

The battlefield is fast becoming "integrated," whether the communications involve interoperability with other services, situational awareness, tactics, collateral damage, fratricide, rules of engagement, mobility, survivability, or lethality. SLAD should be looking to expand its tools and expertise in order to help its Army customers address survivability and lethality in an integrated fashion in this complex network of systems. Areas in which SLAD is already working and that merit further, in-depth involvement are described below.

SLAD should conduct more work in interoperability. SLAD has good knowledge of interference with Army radios, but it seems to have done very little to share this knowledge with the other services.

As joint operations become the norm, interoperability will become critical for effective operations. Because the Army will be "at the business end" of many joint operations, it is imperative that the Army take the lead in this area. SLAD needs to recognize that this is a critical element of operational T&E, and it needs to take appropriate measures to incorporate interoperability into its test programs.

## Combat Systems Research

As an organization, SLAD seems focused on survivability—for example, collecting vulnerability data and developing vulnerability algorithms—far more than on lethality. SLAD seems to address survivability as an entity separate and isolated from lethality. Collateral damage was not mentioned in any of the programs reviewed, but this is a critical consideration when evaluating lethality. It is becoming an issue even with survivability (e.g., active protection systems). Survivability is strongly tied to tactics, visual/infrared/electro-optic/radio-frequency/audio signatures, survivability systems (APS), and host-platform vulnerability. In most cases SLAD is aware of these other considerations but is not addressing them in an integrated fashion. SLAD should broaden its perspective by starting to consider what kinds of analysis tools, expertise, and products will be needed for future Army programs, and then it should start preparing roadmaps for the development of those capabilities. For instance, unmanned aerial vehicles (UAVs) were shown as part of the integrated FCS environment. Much work on UAVs is being done by the other services (and associated laboratories). SLAD effort to leverage these activities was not in evidence.

Combat systems research at SLAD has migrated toward mine-resistant ambush-protected (MRAP) modeling and live-fire analysis as the need has emerged. This migration is very responsive and critical to informing system acquisition. The SLAD desire to extend models to be predictive with respect to vehicle and personal damage and/or injuries should be supported. Just as in ARLTAB reviews in previous years, a major bottleneck in the flow of analysis is CAD data conversion and the staff time required to review and validate input data. The Ballistic Research Laboratory (BRL)-CAD project should receive support to continue its progress in the area of CAD data conversion. The major technical gap in this area, with the largest potential payoff for support to current operations, is in the predictive modeling of underbody blast. This is a nontrivial technical problem; a multiyear program is underway to deal with it.

The development of underbody blast methodology is well thought out and fills a critical need in the assessment of underbody blast vulnerability. It is a good example of research that could have an impact on the next generation of vehicles, or even on refinements of current production vehicles. A number of detailed research problems, including the effect of geometry on the coupling between blast and structure, need to be undertaken to improve the fidelity of the codes.

## Simulation Tool Development

The Information and Electronic Protection Division is extending SLV capabilities into earlier stages of program development. This is commendable and should be encouraged. SLAD has many capabilities and much expertise that lend themselves to early product development. IEPD is already doing this on selected programs, but it could be extended throughout all of the division's technical areas. The goal of simulation-tool development should be to enhance the simulation and predictive capability so that less laboratory and field experimentation is required (only enough to validate predictions). The use or development of a modular code would help accelerate the simulation-tool development process. Also important here is the need to do regression testing of deployed technology against new or modified threats. SLAD needs to develop a test methodology that includes full regression testing against all variants of the products that it has fielded and a communication and update mechanism for the users of those products.

### Countermeasure Capabilities

SLAD has a very capable missile electro-optic countermeasure (EOCM) simulation capability, testing methodology, and set of experienced personnel. SLAD personnel have strong contacts with other DoD organizations involved in missile EOCM testing, and they are recognized within the defense industry as a key player in the field. SLAD's activities and knowledge base are focused on Army EOCM system testing for established programs, which is appropriate, because such work is within SLAD's basic charter. Even so, SLAD has contacts within industry and is currently involved in a cooperative test program with a defense contractor investigating an advanced EOCM concept for a ground-based threat response system. This effort is commendable, and it should be taken further.

SLAD has the opportunity to develop additional knowledge and expertise by expanding its awareness of non-Army programs, capabilities, and advanced concepts. For example, SLAD was not aware of an AFRL program called the Laser IRCM (infrared countermeasures) Flyout Experiment that developed and tested a prototype of a closed-loop infrared countermeasures capability for large, fixed-wing aircraft. This technology could have application for Army platforms and should be considered. All of this information has been openly discussed at conferences and is readily available on the Internet, yet SLAD personnel were not aware of it. SLAD would benefit from becoming more involved and aware of non-Army EOCM programs and the lessons learned from those programs. Attending conferences is an obvious means of expanding this awareness. SLAD should also seek out information on advanced concepts and roadmaps from its DoD colleagues.

SLAD should place additional emphasis on the field of directed energy (DE). There is some awareness of this field within SLAD leadership (for example, in the Counter-electronic High Power Microwave Advanced Missile project and other high-powered-microwave and high-energy-laser efforts), but the awareness needs to be spread to lower levels of the organization. There are not many U.S. programs in DE at present, but the awareness is only a matter of time before DE capabilities transition to the field and DE threats proliferate. Now is the perfect time for IEPD to build up capabilities and expertise, develop professional relationships, and start thinking about possible collaborations. This would be a perfect area of involvement for some of the division's early-career personnel. There are dedicated DE conferences sponsored by the Directed Energy Professional Society (www.deps.org) that IEPD personnel can attend.

Collaboration and coordination of EMVAF programs with other services (the Air Force and the Navy) should be continued, cultivated, and encouraged for the development and evaluation of capabilities. Modeling and simulation tool development should be encouraged. Successful development could help in the validation of data and lead to predictive capabilities, which would make this facility an unrivaled resource in DoD. Validated modeling and simulation tools could also eventually be incorporated into SoSA (S4), providing enhanced capabilities for analysis and decision making.

### Warfighter Survivability

The Experimental Techniques for Helmet Testing Program provides an excellent opportunity for SLAD to collaborate with outside experts to define and conduct further research to characterize fully all of the variables that might be important in the analysis of test results. There is a need to define more analysis parameters for a better understanding of the standard test method relative to field data. There may be parameters other than those defined thus far that would make more sense for comparisons. There are a number of research opportunities that could result in a markedly improved understanding of the protection of personnel. These include the development of scaling laws for gel blocks in terms of energy absorption, the dispersion of momentum through the study of wave propagation using high-speed photography, and the validation of penetration models used in simulations by cross-comparison. The work on helmets can be expanded by including the characterization of materials at strain rates relevant to the application, a systematic examination of the role of composite structure on energy absorption, and an assessment of damage using nondestructive evaluation (NDE) techniques. It would be useful to provide measures for the uncertainty quantification of the parameters that are being measured. In armor testing, SLAD does not characterize the samples to gain an understanding of the lot-to-lot variability and the effect on scatter in the data. It would be useful to see the development of some sort of NDE methodology for this as well. Both the helmet testing and armor testing are very solid efforts, but there is much more room for defining research programs around these projects.

### Active Protection Technology

The Army and its contractors are developing active protection system technologies to augment the armor protection on combat vehicles. To support the assessment of APS technology, the U.S. Army has developed an end-to-end model for APS systems. SLAD has defined its role as being a major partner and contributor in the APS effort, working to assess the following: the effectiveness of APSs against all of the threats in the class that the system is designed to defeat, the ability of the systems to function against potential threat countermeasures, and the potential vulnerabilities introduced to a host platform by an integral APS. However, the SLAD presentation of this program did not support many of these claims and, in fact, conveyed the distinct impression that SLAD is not yet fully engaged in the end-to-end analysis of active protection systems. It seems clear that SLAD is addressing gaps in the APS modeling capability, which is something that SLAD does particularly well and in which it is likely to make significant contributions. Although SLAD has expertise that can be brought to bear in certain technical aspects of the modeling effort, it is not at all clear that SLAD has the necessary knowledge or experience to do a thorough, system-level analysis. This is a key shortcoming that SLAD should attend to sooner rather than later. System-level analyses are becoming more important to Army programs, and SLAD needs to develop this capability soon or risk losing the pace required for understanding this emerging element of survivability.

### Information Operations

SLAD does not seem to have ready access to classified information or data in the area of information operations, which prevents collaborations with the appropriate contacts. Interaction with the intelligence world is paramount for ensuring that SLAD has access to the classified information needed to develop the state-of-the-art vulnerability models for current and anticipated threats. It was obvious from many of its presentations that SLAD does not have clear inroads into the world of classified information. Remedying this need must be driven from the top down. The resistance of the Deputy Chief of Staff, G-2, U.S. Army, whose area of responsibility is intelligence, and of the Chief Information Officer, G-6, whose area of responsibility is information management, to unconventional threat concepts was identified during this review period as a problem, as was the fact that SLAD cannot talk directly to the all-source intelligence community. It also appears that SLAD may lack a sufficiently high degree of access to classified facilities and communications, which is a serious concern, given that all credible sources of intelligence and live operational planning are Top Secret-Sensitive Compartmental Information and are thus compartmented. SLAD seems not to know how to engage the intelligence community. SLAD should follow up on and look for opportunities to interact with the U.S. Strategic Command, the unified major command at Offutt Air Force Base, Omaha, Nebraska; and also with the U.S. Cyber Command, located at Fort Meade, Maryland (by moving up through the Army G-6, which is in the process of developing an Army Cyber Warfare Doctrine). If SLAD finds it difficult to form direct relationships with these organizations, then it should seek partnerships with laboratory organizations that have those relationships, such as the Department of Energy laboratories. SLAD's superior chain of command eventually intersects with authorities capable of forging needed relationships, but SLAD will have to initiate and justify requests for such interaction.

SLAD has an established methodology for SLV analysis that has worked very well in the past, but this methodology may not be fast enough for information operations (IO). The IO threat can change rapidly, and the methodology requires constant updates to remain effective. SLAD should increase its visibility in the cyberthreat community. It should look to initiate partnerships with organizations that have appropriate knowledge (e.g., the Strategic Command) and the specific networks as they are fielded. These relationships may take substantial time and effort to build, but doing so may prove exceedingly worthy goals.

### System-of-Systems Analysis and the System of Systems Survivability Simulation Tool

SLAD is very much analysis-based and fulfils an important role for ARL and the Army in studying, testing, and evaluating weapons systems for vulnerability and survivability. By comparison, the system-of-systems (SoS) concept, as SLAD conceives it, is at a higher conceptual level, more focused on a larger-scale combat-modeling framework. This is very different from the modeling performed by the current SLAD organization and will require additional investment in personnel resources and time to gain the level of expertise necessary to be on par with existing capabilities within the directorate. The S4 initiative is aimed at providing extended support for analysis and evaluations of larger-scale integrated systems that incorporate more behavioral system interactions and dynamics into the decision making. There are serious issues in SoSA and S4 to be clarified and justified.

The problem context for SoSA has not been clearly presented. The program description gives the impression that SLAD is taking on the SoS analysis problem in general, rather than tactical engagement problems at the Army brigade level and below, and perhaps even more narrowly, utilization of Future Combat Systems. SLAD should first present examples of SoS problems that ARL seeks to address, and then move into the analytic approaches that are considered effective for this particular domain and class of systems.

From a modeling and analysis point of view, SLAD's program scope as it is today provides SLV analysis and evaluation support for a range of equipment, processes, and weapons systems. Three issues motivate SLVA: (1) identify system weaknesses, (2) identify adversaries' capabilities to exploit, and (3) determine the relative impact or consequences of exploitation. These issues are direct parallels with the widely accepted Failure Mode, Effects, and Criticality Analysis in product and system reliability engineering design and analysis. This is reasonable and seems to be consistent with the current methods employed in SLAD. The SoSA initiative is aimed at providing extended support for comparable analysis and evaluations of larger-scale integrated systems that incorporate more behavioral system interactions and dynamics into the decision making. There is a concern that the direction for the SoS framework and philosophy is to develop a platform for the analysis and evaluation of SLV without a specific plan. The concept is a good philosophical approach for describing the integral features of a complex system in terms of the physical elements, cognitive processes and/or domain, and context realization. What are lacking are the details that address the objectives, requirements, and operational level for SoSA model development:

- What is the purpose and value of the SoSA concept?
- What does this concept provide that is at present not available for carrying out the SLAD mission for analyzing and evaluating survivability and vulnerability?
- What is the plan for incorporating or transitioning into this new broader framework, and how will this improve the results of the analyses and evaluations for vulnerability?

During this review period the SLAD presentation of its approach to SoSA provided a description of the management oversight process, but issues and concerns still apply:

- What are the survivability questions to be addressed by the modeling effort?
- How much granularity is necessary to address the issues?
- What assumptions can be accepted, verified, and/or confirmed?
- What level of confidence is permissible for the SLV decisions?

There is need for a concise plan that includes the rationale for the use of SoSA in SLAD; the plan should indicate how the use of SoSA will contribute to the SLAD mission and identify the technical-personnel support necessary to sustain the function. This plan needs to define how SoSA tools will be established and implemented and to identify one or more specific applications that will prove the worthiness of this tool relative to the SLAD portfolio.

It seems that SLAD is taking a broad and general approach to developing this SoSA tool without a plan for how it will be used in such a way that results can be interpreted meaningfully. This initiative can be viewed as a large experiment, with many factors (independent variables) that can be varied purposefully or randomly and with many dependent variables that can be measured and used variously as objective gauges. SLAD has presented no evidence that it shares this view or that it is concerned about designing experiments so that results can be statistically evaluated. To do so is technically and computationally quite challenging, but it is essential if SLAD is to claim any result of scientific consequence.

In developing such a complex tool, it is imperative to identify near-term and long-range goals and to establish a well-defined set of success metrics against which to compare progress. SLAD mentioned that a proof-of-concept analysis is being established. This is a very sound idea; SLAD should rethink this program and take a "Hudson's Bay Start" (finding and fixing problems early through smaller first steps) to fully assess the feasibility of its approach. SLAD should demonstrate the feasibility of its tool-development methodology on a small, well-defined problem or case study for which the variables and uncertainties are mostly well understood, with a clear, concise description of exactly what information needs to be provided as input and what is expected as output. This requires a sound definition of the customer and of the problem to be addressed. In this manner SLAD can develop confidence in its tool-development methodology before committing vast resources to this effort. Once SLAD has successfully demonstrated the feasibility of its methodology, it can work toward expanding the tool set to perform analyses of a broader range of systems, subsystems, and threats. As a start-up in a nontraditional area for SLAD, this project must have three goals: (1) to make contacts and establish credibility inside the Army, (2) to achieve recognition in the wider scientific community, and (3) and to obtain well-understood, useful, statistically justified, trustworthy technical results. A short-duration, well-defined, proof-of-concept analysis accomplishes these goals without impeding progress toward achievement of the long-term goals.

There is a concern that individual SLAD analysis codes are implemented within S4 mainly because they are available and the S4 staff has the time to do this work. SLAD should apply a more disciplined approach, wherein a new code is integrated when it addresses a known accuracy bottleneck, and its performance is tuned to the level of accuracy needed by S4.

Specific concerns regarding SoSA and S4 include the following:

- *Adaptation and reliance on SoS as a methodological framework and reliance on red team analysis for threat modeling.* The SLAD approach to survivability analysis with regard to information operations is fundamentally flawed. It relies almost exclusively on red team analysis. There are two problems with this approach as practiced. First, the red teams should be used as an adjunct to formal threat-modeling and remediation techniques. In theory, a red team exercise will discover threats that were not sufficiently modeled using other formal methodologies. SLAD should adopt one of the several generally used threat-modeling methodologies. Second, there is insufficient input from the various intelligence organizations on the nature of current threats for creating an adequate basis for either threat modeling or red team operations. IO is a very fast-moving environment, and the nature (source and method) of attacks changes quickly. Everything that SLAD is working on in this arena is almost 2 years old. SLAD should create partnerships with the National Security Agency (Network Tactical Operations Center, Technical Access Operations, Advanced Network Operations) and the Central Intelligence Agency. Acknowledging the difficult and time-consuming nature of the task, it is worthwhile for SLAD to initiate these partnerships.
- *Acceptance and understanding of the use of and limitations to agent-based modeling.* SLAD's current implementation plan relies heavily on agent-based simulation, originally developed at the Santa Fe Institute. In professional hands, agent-based modeling can explain the "what" of some situations—that is, it can sometimes reproduce observed results—but that can be of limited value, because it does not explain the "why." Agent-based models in inexperienced hands have produced embarrassing failures. Proponents sometimes make much of the fact that such simulations can cosmetically exhibit large-scale behavior that is complex, but of what value is that if the model does not explain why the complex behavior is happening? As a general observation, agent-based modeling can be valuable even when it yields only qualitative results. For example, agent-based models in behavioral economics have been used successfully to choose between proposed structures for markets and regulation of markets, even though these simulations cannot be validated quantitatively.
- *Information assurance is not treated strongly enough in the current cyberthreat environment*. There is concern that insufficient priority is being given to SLAD's information assurance practice, given the current cyberthreat environment. There is a potential to have broad foreign intelligence penetration of SLAD-delivered solutions if the information assurance methodology is not robust enough. SLAD needs to adopt, as soon as possible, a security development life-cycle model for the development of its code and systems. Historically, DoD self-created systems have proven very insecure. SLAD should also have a relationship with the National Visual Analytics Center at the Pacific Northwest National Laboratory.
- *Lack of collaboration and tie-in with the intelligence community.* SLAD creates a relatively small set of stable threat effects and models those reliably in the SoS. Although this is a valid approach, it should always be used with caution because of the problems associated with using models describing the vulnerabilities of individual components in order to predict the behavior of whole systems. The approach taken elevates the analysis to get around this problem by looking only at the effect of the attack on a component, not the method of attack at all. The risk that SLAD runs, and it is a recurring theme, is that it does not have actual intelligence data on which to base its analysis. Current silent Trojans and supply-side attacks against network interface cards and routers come to mind as examples of attacks needing analysis for which SLAD does not have access to intelligence data.

- *Lack of collaboration and relationships with the complex-systems-analysis community.* SLAD should establish a partnering relationship with the Naval Postgraduate School and other organizations leading the charge in complex systems analysis.
- *Uncertainty analysis not well defined*. So-called systems of systems generally contain enormous amounts of variability. Such systems can be made to do many different things by adjusting the individual components differently, and these systems are so complex that the connections between individual components (e.g., agents) and overall system behavior are not at all clear. SLAD needs to detail how uncertainties are incorporated and accounted for within each model. The phrase "managing uncertainty" as used in this review must surely include dealing directly with uncertainty issues, but there is no evidence that the S4 project has done so yet. S4 is a complex simulation, with multiple levels of granularity and complex interactions between different types and levels of simulation. A serious effort must be made to track how errors propagate and accumulate in the system.
- *Verification and validation studies and sensitivity studies not well defined*. There appear to be scores, if not hundreds, of control variables that need to be systematically explored before analysts make any judgments about model results. This exploration is an essential precursor to any V&V effort. Unfortunately, without hard basic thinking about just what information the SoS model will provide, how sensitive it is to input assumptions, how to interpret its outputs, and other basic issues, SoSA demonstrations are likely to be largely meaningless. Sensitivity to inputs is a substantial issue, and experimental design can contribute to an understanding of the model's sensitivity.

A major hurdle that the SoSA project must cross to be successful and relevant is to demonstrate an ability to extract useful information from large numbers of Monte Carlo simulations of time histories. This is a challenging problem, and if the S4 staff can make good progress in this direction, it will make a major contribution to the field. The families of metrics that have been defined are clearly intended to be a start in this direction, as are the graphical techniques that highlight these metrics and leverage human pattern recognition capabilities to sort through the S4 output, but it is not yet clear that these are the right metrics, or that effective means of understanding their distributions and correlation structures have been found.

SoSA is driven by the analysis question being asked, and it is inherently multidisciplined. SLAD wants to develop a distributed, collaborative environment. If these points had been made upfront and put into the Army tactical engagement context, they would have served to guide the SLAD staff better in their SoSA characterizations and in focusing their work. They are useful points to keep in mind as one develops an SLAD SoSA approach, but that approach either does not yet exist or was never articulated.

Systems engineering practices should be a foundation of SLAD's institutional approach as a complement to a well-defined design for SoSA modeling tailored to the Army's modern tactical engagement problems. This may not be feasible within SLAD's resources. There is need for an organization within the directorate that supports the modeling, methods, and analytical needs and which interacts with other ARL directorates for new initiatives, but such an organization would look very different from the current SoSA effort.

The SoSA project is the largest research area in which SLAD tries to interact with academia or with outside researchers to gain information on how best to do things. SoSA is SLAD's largest tool. SLAD is still relying solely on the Physical Science Laboratory at the New Mexico State University to develop the System of Systems Survivability Simulation (S4) tool, but it has started the process of developing collaborations both within and outside the Army (e.g., with the Navy and academia). SLAD should try to make use of interactions with the Defense Advanced Research Projects Agency (DARPA) panel on complex systems, although it is recognized that interactions with DARPA can be difficult. There are also many academic programs being initiated in complex systems with which SLAD can interact. SLAD should consider trying to attract postdoctoral students or visiting professors who are expert in the various fields of interest to SLAD. It is acknowledged that it may be challenging to attract experts of this type, because the constrained topic area of survivability/lethality is not a widely addressed research topic and because much of the SLAD work may be classified and therefore difficult to publish in conventional journals.

The Board has requested that SLAD address the questions and suggestions above in a special meeting scheduled for January 2011 and in the next review meeting, scheduled for August 2011. It is expected that these meetings will include discussion of ways in which SLAD's core competence in component modeling can best be merged with and support system-of-systems modeling, and where the bounds of SLAD's activities in system-of-systems analysis should be set.

## MUVES 3

MUVES 3 was presented to the panel as the vehicle by which SLAD's MBT&E analyses are going to be conducted. Analyses start with BRL-CAD drawings of all of the vehicle components of interest: a library of penetration models, a library of damage models, and then an assessment of a "kill" is made of component, soldier location, or other element of interest. This code presents an admirable capability for using a high-resolution, high-fidelity simulation to support a reduction in the number of live-fire tests required to fully bound component damage due to various threats. This program has made great strides in the past several years, but there are still several areas of concern.

This is a large model that combines many components with no clear summary on how the various pieces are linked in order to produce an accurate representation of system behavior and outcomes. SLAD personnel have developed a set of well-defined case studies with a given set of input information and expected outcomes, but there is no clear plan for conducting sensitivity studies or accounting for variable and model uncertainties. Will importance sampling be used to reduce the required number of code runs to assess the sensitivity to the various parameters?

SLAD has defined S4 and SoSA as a user of this code, but no plan was apparent for how MUVES 3 will be fed into these force-on-force models. Will there be other users of this model? If so, how will user requirements be defined and implemented into the model? These considerations need to be included in the plan for moving forward with MUVES 3 development.

MUVES 3 would be better presented as a cohesive initiative rather than as a number of components and notions for their future integration. MUVES 3 would also be well served by formal organization of its contributing professionals, with a single leader knowledgeable about all of its aspects. For an initiative of such ambition, a star technical leader would be invaluable for leading and coordinating a wide variety of supporting technical work and for representing the program to Army clients, leadership, and external reviews such as the one performed by this panel.

## OVERALL TECHNICAL QUALITY OF THE WORK

The charge of the Army Research Laboratory Technical Assessment Board includes assessing the technical merit of the work performed in each of the ARL directorates against that of leading federal, university, and/or industrial laboratories both nationally and internationally. In contrast with the program portfolio of many of the other ARL directorates, the SLAD program portfolio includes relatively few applied research programs and no basic research program. The vast majority of SLAD programs are funded at much later stages in the DoD research, development, testing, and evaluation chain supporting acquisition and deployment programs. The SLAD portfolio and evaluation structure are based strongly in the directorate's long history of ballistics-based vulnerability assessment. It is commendable that SLAD has broadened its program base to include assessment of communication, network, and information-processing vulnerability on the battlefield; nonetheless, the efficacy of the SLAD tool development methodology may not be sufficient to identify and stay ahead of the rapidly emerging threats to network-centric warfare in an irregular battlefield environment.

The panel was asked to evaluate the performance of SLAD relative to how its people, infrastructure, and technical programs match up with the greater science and technology community. In past reviews as in the present assessment, this task has been and continues to be a source of angst, since SLAD seems rooted in a solid engineering paradigm. SLAD is excellent at understanding and applying sound scientific principles in developing engineering solutions to applied problems, but in order to remain effective in assessing vulnerabilities due to rapidly emerging threats in network-centric warfare, SLAD should work toward leading the way as the recognized innovator in the field in tool-development methodology. This requires a well-defined *research* program that focuses on expanding basic scientific principles into sound, comprehensive, flexible tools, and it includes full participation in the global research community through collaborations, interactions at conferences, documentation and publication, and staffing that includes people well trained in the scientific principles needed to advance the state of the art in tool development. It is clear from presentations to the panel that SLAD personnel are much more confident in the technical engineering programs than in those dealing with conceptual work or system modeling. The reason may be their comfort with using well-understood principles to deduce how physical systems will behave in specific situations, as opposed to their seeming discomfort in areas such as systems modeling, in which such well-understood scientific principles do not yet exist.

The focus on research (applied and fundamental) within SLAD is relatively low. This is exacerbated by a low percentage of Ph.D.'s on the staff and relatively little collaboration with the external community, including academia and other research laboratories. The age pattern of the SLAD workforce is also a concern. SLAD should look toward postdoctoral, sabbatical, internship, and visiting scholar programs to provide healthy intellectual input and invigoration. In the short term, SLAD should expand its postdoctoral program to bring in personnel trained in areas of need. This might best be accomplished through the National Research Council program of which ARL is a member. More personnel from SLAD should be encouraged and incentivized to pursue advanced degrees (M.S., Ph.D., and post-degree sabbaticals) in relevant areas. Partnering with the Army Research Office to fund programs including 6.1 research and Multidisciplinary University Research Initiatives in areas of interest to SLAD would help in training and recruiting personnel. Establishing centers of excellence in universities in the vicinity of SLAD can also help in these areas.

Collaboration and participation with the greater technical community are essential components of any research program. Collaboration enables the leveraging of SLAD facilities and expertise to gain diversity and expanded capabilities. There still does not seem to be significant collaboration with outside researchers. It seems that SLAD does not understand the depth of the panel's comments on insularity; it is not just about attending conferences and working with other groups that do similar activities, which at times SLAD does well. Collaboration is also working closely with industry on joint projects, exploring new and innovative ideas by means of exploratory research projects with academia, or developing methods for enhancing survivability and lethality in joint projects with national laboratories. Telephone conference calls and briefings are a very weak form of collaboration, and many of the reported collaborative efforts sounded more like customer-client relationships. Although there were several indications of improvement in collaboration and partnering with other organizations, SLAD needs to provide a clear demonstration of the sharing of resources and assignments between parties of a defined collaboration.

SLAD personnel need to document their work much better, including their innovations and test methodologies, instead of framing their documentation as internal progress reports. To become the leader in any field, they need to generalize their work enough to publish it, especially lessons learned! They should be keeping their innovations and test methodologies in some sort of ongoing documentation. "Publication" has been widely defined by SLAD to include a few open-literature publications, some technical reports of unknown provenance in regard to critical technical review, and many internal documents and presentations. There is a lack of scientific or technical peer review and thus scant traditional independent evidence of the rigor, efficacy, currency, correctness, and technical quality of the work.

Entry into certain communities can be very difficult unless one is contributing to the research. Small Business Innovation Research programs provide opportunities for collaborating with industry to do unique research with relatively little effort. SLAD personnel and programs should be taking advantage of University Affiliated Research Centers, including those in biotechnology and in soldier survivability. SLAD should approach the Department of Homeland Security; they both should be able to collaborate in the area of survivability and lethality, possibly through other national laboratories. SLAD should work with its contractors to define DARPA-funded survivability programs.

The Survivability and Lethality Analysis Directorate provides sound support of the assessment and evaluation of the survivability, lethality, and vulnerability of Army equipment and soldier systems to ensure that soldiers and systems can survive and function reliably in the full spectrum of battlefield environments. The directorate is well staffed with bright, creative professionals enthusiastic about their mission, and its facilities include state-of-the-art laboratories. SLAD has many opportunities to expand its testing and evaluation base through select program expansion aimed at developing tools and methodologies to broaden its analysis capabilities and to define and maintain the competitive edge required to be the Army's primary source for SLV assessment. The SoSA and MUVES 3 programs continue to be of concern, but with appropriate focus these programs can grow to become foundations of the SLAD analysis capabilities.

# 6

# Vehicle Technology Directorate

## INTRODUCTION

The Vehicle Technology Directorate (VTD) was reviewed by the Panel on Air and Ground Vehicle Technology of the Army Research Laboratory Technical Assessment Board (ARLTAB). The directorate has four divisions, three of which are aligned with the key scientific disciplines of mobility: Propulsion, Autonomous Systems, and Mechanics; the fourth division is the Vehicle Applied Research Division (VARD). VARD provides an early assessment of evolving technologies to aid the directorate's investment decisions and to ensure that all technologies required for a class of vehicles are covered, and in general it increases the research productivity of the entire VTD. In addition, two Collaborative Technology Alliances (CTAs) are an integral part of the directorate. The directorate leads the Robotics CTA and participates in the Micro Autonomous Systems and Technology CTA, acting as the point of contact for the Micromechanics Center (led by the University of Maryland). All divisions of VTD and portions of the CTAs were reviewed by the panel.

Appendix A shows the staffing profile for VTD (see Table A.1). The assessment below reflects visits by the Panel on Air and Ground Vehicle Technology to the VTD sites at NASA Glenn Research Center on July 13-16, 2009, and at the Army Research Laboratory (ARL) facilities at Aberdeen Proving Ground, Maryland, on June 8-11, 2010.

## CHANGES SINCE THE PREVIOUS REVIEW

Many changes have occurred in VTD in both manpower and research as well as its location since the previous ARLTAB report.[1] The directorate is benefiting from leadership that has seized the opportunity

[1] National Research Council. 2009. *2007-2008 Assessment of the Army Research Laboratory.* Washington, D.C.: The National Academies Press.

presented by the consolidation required by the 2005 Base Realignment and Closure (BRAC) decision to develop and motivate a unified team around a research portfolio focused on the critical Army need of ground and air vehicles, with a current focus on relatively small vehicles. Although the hiring of new team members and the transition of the research portfolio from a focus on large, helicopter-type vehicles to a focus on the smaller ground and air vehicles have not been completed, there has been much progress on both of these issues in the past 2 years.

Currently three of the four VTD divisions are located at Aberdeen Proving Ground, and the fourth is in the process of locating there. In addition, VTD has in place a Memorandum of Understanding with NASA for the 11 VTD staff members who will remain at the NASA Glenn Research Center or the NASA Langley Research Center. This Memorandum of Understanding gives VTD the advantage of having access to unique facilities and personnel at the two NASA sites. At Aberdeen Proving Ground, construction is under way to house VTD personnel and corresponding research laboratories. The new building is scheduled for occupation in time to meet the date mandated by BRAC.

During this 2009-2010 review period, the most far-reaching change to VTD has been the development and staffing of VARD. The creation of this new division is in direct response to concerns expressed by ARLTAB in its previous report.[2] That report urged VTD to maintain a systems focus as it instituted changes in its location, personnel, and research portfolio over the 2009-2010 period. With respect to its research portfolio, VARD has used integrated systems analysis to define eight capability concept (CC) vehicles that address defined Army objectives and critical capability needs (see Figure 6.1). VTD management is in the process of aligning its research portfolio to address the technologies required to meet the requirements of the eight capability concept vehicles.

## ACCOMPLISHMENTS AND ADVANCEMENTS

Significant technical transition has been achieved by the divisions and several programs during the past 2 years. The status of these accomplishments and advancements is discussed below.

VTD's most far-reaching accomplishment in the past 2 years has been the development by VARD of the eight capability concepts. These eight CCs cover the Army's objectives and critical capability needs, make a clear statement of VTD's vision to meet the Army's needs, and serve as a clear guideline for individual researchers to align their research to these needs. The CCs also allow VTD management to prioritize research that will impact more than one CC and to determine quickly if its portfolio of research is sufficient to meet the technology requirements of the capability concepts. The focus provided by the CCs will serve as a valuable yardstick for VTD as it continues its efforts to develop an excellent research portfolio in the new focus area of small autonomous air and ground vehicles. Because VTD is in the process of changing to the capability-concept-driven research portfolio, the discussion below is organized to present the status of the research and progress of an example capability concept and related general accomplishments.

### Examples of the Persistent-Staring-Vehicle Capability Concept

The goal of VTD's research portfolio for the persistent-staring-vehicle capability concept is to reduce the weight by a factor of two and increase the time on station by a factor of five relative to a referenced vehicle. VTD's research portfolio for this capability concept includes a pressurized-structure vehicle, powered by advanced internal combustion engines, ceramic engine components, flash-vaporized Jet

[2]Ibid.

| Capability Concept | Army Objective | Critical Capability Needs |
|---|---|---|
| Persistent Staring ISR | Improved and persistent situational awareness for military operations | •High endurance VTOL<br>•Autonomous operation |
| Cargo UAS | Overcome sustainment shortfalls associated with current supply methods | •High speed VTOL<br>•Autonomous operation<br>•Automated cargo handling |
| Multirole/ISR Attack VTOL | 6K/95 armed aerial escort with higher speed/longer range than current fleet | •Variable speed power/drive<br>•Adaptable rotor performance |
| Long Range Heavy Lift | Mounted vertical maneuver into austere environments | •Large stable rotor<br>•Large efficient propulsion<br>•Lightweight durable structure |
| Advanced GCV with UGV Wingman | Improved survivability and mobility for armored vehicles | •Reliable efficient propulsion<br>•Armed robotic vehicle |
| Terrain Adaptable TWV | Tactical transport with robust mobility in austere terrain | •Reconfigurable suspension<br>•Advanced high power diesel |
| Small Dexterous Robots | Soldier tasks performed at a safe stand-off distance | •Higher levels of autonomy<br>•Dexterous manipulation |
| Micro Autonomous Systems | Tactical situational awareness | •Low-power mobility<br>•Distributed autonomous ops |

FIGURE 6.1 The mobility capability concepts approach of the Vehicle Technology Directorate. NOTE: Acronyms are defined in Appendix D. SOURCE: Mark Nixon, Vehicle Technology Directorate, "VTD Overview," Presentation to the panel, Aberdeen Proving Ground, Maryland, June 8, 2010.

Propellant 8 (JP-8) fuel injectors, a ducted fan with diffusing exit contours, and an autonomous control system. Systems analysis by VARD has demonstrated that if this research portfolio were successful, the performance goal of the persistent-staring-vehicle capability concept would be achieved.

Preliminary investigations have identified ultrahigh-molecular-weight polyethylene as a material having the weight and strength characteristics necessary to meet the goals for a pressurized-structure vehicle. Plans are in place to characterize this material in different structural forms and to construct prototype air vehicles with the material. The construction of a test stand to evaluate the vehicle and its propulsion requirements is planned for FY 2011. The pressurized-structural-vehicle concept appears promising, but a materials expert should be engaged to ensure that the selected materials are robust under exposure to chemicals, ultraviolet radiation, and other relevant battlefield conditions.

Research is underway to develop a computational fluid dynamics (CFD) design system for ducted fans and diffusion exit passages. Both of these technologies are utilized to improve the thrust efficiency and reduce the power requirements relative to the reference vehicle. CFD analysis has produced design shapes for the fan airfoil profiles, and continuing CFD analysis is in the process of defining an optimum fan diffuser exit duct. A fan center body should be included in the design space to ensure that the CFD design system for diffusion exhaust ducts will work for all fan-drive systems.

Both nutating and Bonner advanced internal combustion engines are under development through Small Business Innovation Research (SBIR) funding. These engines, if successful, would increase the horsepower-to-weight ratio and improve fuel economy relative to the referenced persistent-staring-vehicle power plant. Both of these engine types are currently at the prototype stage, but neither has demonstrated the achievement of its design goals. These engine configurations are of interest because of their novelty and the enthusiasm of their proponents within VTD. However, both the nutating and Bonner engines have remained at the prototype stage over the past 2 years, and the VTD researchers have made little progress toward their design goals. These engine concepts may never reach their design goals, particularly in sizes that are of interest to VTD. Therefore, both the thermodynamic and combustion analysis of the two engines should be done to ensure that these concepts can meet VTD's goals.

Research with respect to utilizing bulk ceramic components in the combustion or rotor sections of engines is being conducted. Bulk ceramic or ceramic composites will be required in engines that achieve JP-8 combustion in small volumes and engines that operate at very high pressure ratios. Both of these areas are of great interest to VTD, and therefore research in this area should be conducted. However, the approach adopted in the current program is a continuation of long series of work performed at the NASA Glenn Research Center. Moreover, the approach taken in this project is not addressing the basic problems that are limiting bulk ceramic application. Therefore, it can be seen by the panel that this approach will not advance the state of the art and will not succeed, and so this work should be refocused or discontinued. For example, the Wankel rotor chosen for this study would appear to be a poor choice. It does not take advantage of the high-temperature capabilities of ceramics, and it requires a metal-to-ceramic joint that will prove difficult to achieve. It is also a complex shape, which will prove difficult to fabricate to the required tolerances and will be subject to residual stress problems. Neither the success nor the failure of this project will prove anything, simply because of the small sample size.

Flash-vapor fuel injector configurations for JP-8 fuels are under development. This research includes the modification and testing of an existing fuel injector, the design and testing of a new injector, and in FY 2011 the engine testing of the final selected injector. The burning of JP-8 in all power plants has been defined as a key Army technology goal. The current programs are demonstrative in nature and may lead to some short-term use of JP-8 in some platforms, but given the key technology, classification work needs to be done in the more basic areas of burning JP-8 in small volumes with small residence times. This is a critical research area for VTD—that is, as pressure ratios increase and the size decreases for engines burning JP-8, there is a clear need for fuel injectors of this type. The approach underway does not have a high probability of success; however, this problem is so important that the program should continue, but it should be carefully coordinated with similar work underway in other parts of the Army and in other services. In fact, because of the importance of this research area to VTD, the directorate should commit increased resources to it.

Research to develop control systems that effectively combine manned and unmanned vehicles into an effective, safe, coordinated team is underway. The proposed approach is to use an object-oriented mapping decision process to learn both the types of action that a human would take and the proper control response of the teamed unmanned vehicle. This approach was poorly justified and is not recommended. A better approach might be to provide a set of initial rules of perception and control to the unmanned vehicle and then allow the vehicle to learn and adapt to the unique characteristics of a particular human pilot. More attention should be paid to the challenge of inferring the intention of the human and to how the approach should be formulated to address this key issue.

## General Accomplishments

The Vehicle Technology Directorate continues to perform good work and to make progress in its historic focus area of helicopters and helicopter-size engines while increasing its research in smaller, robotic-type systems. Two examples of good work in the helicopter area are the demonstration of the active twist of a helicopter rotor and variable-speed turbine design. Design and analytical studies have indicated that active rotor twist could increase the maximum gross takeoff weight of a helicopter by 10 to 15 percent. A full-scale design of the active rotor twist concept, complete with control concepts, was completed in FY 2010 and is to be transitioned to NASA and the Boeing Company for manufacturing and testing in late FY 2011. The variable-speed turbine research is aimed at developing turbine airfoils that will maintain the near-constant efficiency of a gas turbine from the design takeoff rotor speed to the cruise and near-loitering condition at 50 percent rotor speed. The analytic results of this research show that turbine blades that hold constant efficiency over this speed range are possible and would increase turbine efficiency at cruise or near-loitering condition by greater than 3 percent. This increase in efficiency would greatly improve helicopter time on station or mission radius. Cascade verification testing of this type of turbine airfoils for losses over the turbine operating range is planned in FY 2011.

In the newer area of smaller air and ground robotic systems, significant advancements have been made by the Robotics Collaborative Technology Alliance. This program continues to be a well-organized and well-executed effort that brings together a consortium of personnel from industry, academia, and government. VTD has two major roles in this CTA—the first is to manage the overall effort, and the second is to test the results of the program. To date, this effort has produced completely autonomous vehicles that have attempted to navigate real-world terrain littered with many obstacles. In addition, this CTA has demonstrated progress in human recognition by an autonomous vehicle in a prototypical complex urban environment. The CTA process continues to demonstrate a great leveraging of Army Research Laboratory money and other resources.

VTD has also made progress in staffing and technical demonstrations in the microrobotics area. This area is now staffed with new investigators who are conducting state-of-the-art studies of the mechanics and function of very small, flapping-winged vehicles. This is groundbreaking research that will have great promise once it is fully staffed and the research portfolio is fully developed. In the robotics area, the overall plan is to build up the robotics activities and to add more people. VTD management did not present a vision describing how the internal robotics research projects are chosen. The articulation of that vision is still a work in progress, as ARL is trying to develop a crosscutting problem but does not have control of all the funds that would be involved. The danger is that the effort will end up pursuing only the technologies that reflect the expertise and interest of the investigators. ARL should pursue strategic planning to design the overall technical objectives of this program so that more-directed hiring can take place. ARL is in need of a critical mass of individuals working in particular areas of robotics that fit into this larger vision. ARL currently lacks a critical mass of technology leaders in robotics. It has a critical need for technical leaders who can provide vision and guidance in the robotics area as well as technical mentorship of the new Ph.D. researchers.

## OPPORTUNITIES AND CHALLENGES

The continued realignment, redefinition, and repositioning of VTD to meet the BRAC requirements as well as its focus on small air and ground autonomous vehicles offer VTD great opportunities to build an organization staffed with excellent researchers who are conducting research focused on critical Army needs.

The standing up of VARD is a first important step to ensuring that VTD is focused on critical Army needs. The challenge now is to ensure that the work of each researcher supports one or more of the directorate's eight capability concepts. In addition, the VTD management team needs to ensure that all of the technologies required for each capability concept are being developed within VTD or elsewhere in the total research community.

By concentrating VTD personnel at Aberdeen Proving Ground, many good early-career and other new researchers are being added in several technology areas. The VTD management challenge is to mentor and guide these individuals to ensure that their research is state of the art and is focused on critical Army needs. This is particularly challenging because many of VTD's new technologies are concentrated in the technology areas for smaller autonomous vehicles instead of in VTD's historic focus area of technologies for large helicopter-type vehicles.

The power per unit of weight produced by JP-8 combustion is approximately two orders of magnitude greater than that produced by battery or electric power. Therefore, the time on station and the range of many of the smaller robotic vehicles would be greatly enhanced by JP-8 combustion in small engines. VTD currently is conducting research into JP-8 fuel injection and is carrying out some research on the operation of current small engines with JP-8. However, this is an area of research that could affect many of the VTD capability concepts and that cuts across many ARL areas. Therefore, this area should be elevated to a major area of concentration for VTD.

For example, VTD should focus on the combustion of liquid fuels in small volumes—that is, in volumes of a cubic centimeter to a few cubic centimeters. Since the energy per unit of mass achievable from common hydrocarbon fuel is more than an order of magnitude greater than what can be achieved with batteries, an attempt to develop efficient and stable combustors of smaller volume could have very great payoffs for small autonomous air and ground vehicles. Also, there can be some improvement over batteries through the use of liquid-fueled (e.g., using methanol or even reformed JP-8) fuel cells. Fuel cells probably will not reach the same power-to-weight ratios as those possible with combustors, because fuel cells rely on surface reactions whereas combustion uses reactions in the open volume. The large amount of internal surface area in fuel cells implies more solid material in a given volume and therefore tends to make fuel cells heavier. Batteries rely on the exchange of charged particles at surfaces and are heavier due to the same surface-intensive cause. In the research on combustion in small volumes, it should not be assumed that the scaling down of processes from large combustors is the logical approach. A critical evaluation of why a process works well at larger scales is urged, as well as some innovation.

The panel commends VTD for its utilization of unique facilities and personnel at the NASA Glenn and the NASA Langley Research Centers. Its challenge, however, is to integrate the research and researchers from these two NASA sites effectively into the VTD organization, with its focus on critical Army needs. This is particularly problematic because many of the NASA personnel have been conducting the same research for many years. On the one hand, for example, the research areas of ceramic components for gas turbines, coatings for small engines, and foil bearings have been ongoing for a long time and have little or no expected use in Army systems. On the other hand, the research conducted by the NASA personnel on compressor-tip-injection stall control is state of the art, but unfortunately it did not find use in the Versatile Affordable Advanced Turbine Engines (VAATE) Program.

The proper balance of analytical work or computer simulation and experimentation in a research portfolio is always difficult. In-house, VTD has more personnel who are capable experimenters than it has capable computation and simulation people. In several research areas VTD has reached out to universities to add computation and simulation to complement good internal experimental research. The compressor-tip-injection stall control work is an example of this combination of experimental and computer simulation. Ensuring that the proper balance is maintained in all research areas is both a challenge and an opportunity for VTD management.

VTD has several research efforts in the prognostics and diagnostics area. This body of research is aimed both at decreasing injuries to personnel inside a vehicle when the vehicle is under attack and at lowering vehicle maintenance cost. This is an area of demonstrated Army need that exists now and will exist far into the future. The definition of a new capability concept of a vehicle health monitoring system and focusing of all research efforts will ensure that the VTD portfolio contains all necessary technologies to achieve this capability concept.

VTD testing and field demonstrations of autonomous vehicles and their interactions with terrain and humans are very important. VTD's Fort Indiantown Gap facility in Pennsylvania is well equipped to conduct this type of research. However, some of the results from recent tests of experiments suggest that the design of the tests and analysis of the data gathered are a challenge for VTD. VTD personnel should develop expertise in the design and conduct of robotics experiments.

There are emergent areas and opportunities for VTD in engineering in mesoscale and bio-inspired systems. These scales represent an opportunity for VTD to take a leadership role. Moreover, this scale of system is likely to be compatible with a multitude of systems for the soldier—for example, squad- or platoon-level reconnaissance assets employing new concepts for air and ground vehicles.

There is a need for the modeling of vehicle systems at VTD. The results of good models, such as performance prediction and scalability studies, seemed absent in many of the projects presented to the panel. Robotic platforms and air vehicles need modeling to enable understanding of performance limits and optimization of platform parameters. Modeling is also critical to system design; good models are the key to insight into the underlying physics, from which meaningful functional and performance metrics can be developed and understood.

VTD should consider undertaking an effort in the following emerging technology areas: mesoscale power sources, such as small fuel cells and gas turbines; the analytical modeling of physical processes such as combustion; and simulators for the training of operators of remotely piloted air and ground vehicles.

High energy density power systems will be a disruptive technology in future Army vehicles. Therefore, VTD should develop and sustain its capability to take a leadership role in some classes of the Department of Defense small engine initiatives. VARD will be of great help in determining in which classes VTD should have the natural leadership role. In order to decide where natural leadership roles exist, VTD should carefully define classes of small engines. For example, a characterization of classes might be as follows: (1) gas turbines: from 3,000 to 10,000 shaft horsepower (hp); (2) internal combustion engines: from 2 to 50 hp; (3) electrical engines: from 0.1 to 10 hp; and (4) hybrid power systems. For example, one area of research that deserves consideration is power sources for baseball-size vehicles. The energy per unit of mass achievable from common hydrocarbon fuel is more than an order of magnitude greater than what can be achieved with batteries. Thus an attempt to develop efficient and stable combustors of smaller volume (a cubic centimeter to a few cubic centimeters) for these baseball-size vehicles could have significant payoffs for small autonomous air and ground vehicles. The number of engine classes needed by the Army and the enabling technology required will exceed the resources of VTD. However, careful selection of primary leadership classes and classes in which VTD needs to leverage the work of other government agencies and industry is the information needed to make the Army an intelligent buyer and will be of great use in focusing VTD's efforts.

The materials science and technology area is of particular importance to VTD. Addressing the need to develop this area requires that personnel embedded in VTD collaborate with others at ARL, universities, and other laboratories. The new VTD laboratory and the embedded capabilities of the Weapons and Materials Research Directorate can be utilized to attract new researchers, faculty, and students for summer internship programs and develop existing personnel in this vital area.

## OVERALL TECHNICAL QUALITY OF THE WORK

The Vehicle Technology Directorate has established the tradition of a research approach that successfully applies analytical tools and experimental techniques in a controlled environment to hardware-based problems of various scales. In many areas, VTD research is contributing to both fundamental and applied levels of technology. In addition, many examples exist of the work of VTD fulfilling both current and future Army needs. Over the past 2 years, a continuum of evidence demonstrating higher-quality research has evolved. The BRAC decision to consolidate VTD at Aberdeen Proving Ground, coupled with VTD management's evolving focus on Army needs, is increasing the quality of the VTD research portfolio. The establishment of eight capability concepts that embody clearly defined future Army needs is a clear example of VTD focus as it moves from research emphasis on helicopter-type vehicles to research emphasis on smaller, autonomous robotic vehicles. The capability concepts approach also improves the quality of the research portfolio by allowing VTD management to ensure that all of the research needed to support each capability concept is underway by the technical community either inside or outside VTD. The recognition that a crawling-bug-type vehicle needs to be added to the Micro Autonomous Vehicle Capability Concept is a clear example of management's understanding of the Army's need in this research area. In a similar manner, the capability concepts approach allows VTD to prioritize research so that research impacting several capability concepts can be moved forward, or research that does not apply to any capability concept might be redirected or stopped. The combustion of JP-8 fuel in a very small volume is an example of a crosscutting technology area that would impact several capability concepts, and it is therefore a high-priority research area.

Some high-quality technical work at VTD is clearly an important contribution to the overall technical community. For example, the compressor-tip-injection stall control work that couples experiment data and computational fluid mechanics is state of the art and will enable the industrial design community to improve gas turbine fuel economy and reduce compressor stall. In a similar manner, the windage work in high-speed gear systems is state of the art and promises to improve gearbox efficiency across a wide range of vehicles. The bearing work offers real increases in power transfer per pound of weight in a large range of geared systems. The 3,000 to 10,000 shaft hp gas turbine (VAATE) program has well-defined metrics; leverages technology development across the Army, Air Force, Navy, NASA, and industry; and, if successful, will enable several classes of new Army vehicles. In all of these areas, VTD is aware of and is leveraging a wide range of government, industry, and university research to achieve the needs of the Army. Clearly there needs to be more work like the examples given above if VTD is going to meet all of its requirements with limited resources.

The VTD research in microautonomous systems is groundbreaking work. The researchers involved in this work are of high quality. The development of a complete portfolio of work in this area and the addition of new team members will improve the focus of this work.

Several areas within VTD are not focused clearly on the Army's highest priorities or are of lower quality than desired:

- The foil bearings, small-engine coating, and ceramics programs need to be examined for relevance to the VTD mission and possibly refocused or eliminated.
- The burning of JP-8 fuel in all power plants has been defined as a key Army technology. The current programs are demonstrative in nature and may lead to some short-term use of JP-8 in some platforms, but given the importance of this key technology, classification work needs to be done in the more basic areas of burning JP-8 in small volumes with brief residence times. This effort

would benefit from being carefully coordinated with similar work underway in other parts of the Army and other services.

- The limiting of equipment maintenance and downtime for unexpected failures is a critical Army need. There are two paths to achieving the desired results: (1) the embedding of sensors to detect impending failures so that action can be taken before the next mission, or (2) the conduct of statistical analysis based on mission usage to determine when to take maintenance action. The current programs are based on the embedded-sensor approach; however, many sensors are less reliable than the equipment that they are attempting to measure, and “low-hanging fruit” from the statistical method is available. Therefore, the research efforts on prognostics and diagnostics should investigate both methods.
- Electric power vehicles will be more commonplace in the future Army. Therefore, VTD should have programs or develop influence and awareness of high energy density for electrical motors, batteries, power conditioning, and control of electric drive trains.

VTD efforts to encourage personnel to participate in conferences, publications, committees in the technical community, and other professional interactions are commendable. Contact with other funding agencies, investigators, and professional societies are essential for VTD to maximize the results of its efforts. Opportunities exist for VTD to increase the awareness of and leverage activities of other agencies and offices; VTD should continue its emphasis in this area. Metrics for success with respect to such opportunities need to be constantly examined in terms of strategic technical goals, objectives, and expectations. VTD presented some very positive results from this activity; for example, the drive train activity includes collaborations with universities in the production of papers, analyses, and experiments. The facilities and intellectual resources of NASA should continue to be utilized as Army representatives in those activities leverage NASA work and capabilities.

The organizational research model of the CTAs is commendable. This model allows the best personnel of industry, academia, and ARL to collaborate on research areas of great interest to the Army. The Robotics CTA is continuing to do state-of-the-art work. The testing and demonstration areas at Fort Indiantown Gap are capable of ensuring that the results of the CTA meet Army needs; however, the current quality of robotic test design needs to be upgraded.

# 7

# Weapons and Materials Research Directorate

## INTRODUCTION

The Army Research Laboratory's (ARL's) Weapons and Materials Research Directorate (WMRD) was reviewed by the Panel on Armor and Armaments of the Army Research Laboratory Technical Assessment Board (ARLTAB) at Aberdeen Proving Ground, Maryland, during July 27-30, 2009, and August 16-18, 2010. The theme of the 2009 review was warfighter protection and survivability; the 2010 review was focused on lethality research and development (R&D).

The Army Research Laboratory is the corporate laboratory underpinning the operational commands for the U.S. Army, and its Weapons and Materials Research Directorate serves as the bridge to the science and technology (S&T) on materials issues supporting warfighter protection and lethality S&T efforts. (Table A.1 in Appendix A characterizes the staffing profile for WMRD.) The overviews presented to the panel in the 2009-2010 period outlined the breadth and scope of WMRD's mission: (1) to support fundamental research (both in-house and through collaborations with academia); (2) to perform evolving research and development; (3) to serve as a "spin-out" resource to develop testbeds, prototypes, and development centers; and (4) to support eventual industrial production of components and systems in the areas of protection and lethality.

## CHANGES SINCE THE PREVIOUS REVIEW

WMRD's principal scope and vision for the future continue to be the importance of materials and manufacturing science and technology for providing the Army with advanced materials and manufacturing science-based solutions that increase lethality and survivability. The 2009 review of the protection portfolio examined a broad overview of how ARL is using its materials science and engineering enterprise to develop technology to increase warfighting ground vehicle survivability and thus protect the warfighter. WMRD articulated the materials-by-design approach employed within ARL, which demonstrated that the directorate's scientists and engineers understand the complex relationship between structure, processing, and properties. Using the various computational tools to help predict material performance shows the staff's excellent desire to increase their fundamental understanding of material behavior and to maximize experimental capabilities and effectiveness.

The importance of high-performance computing in linking experimental facilities to modeling and its validation to WMRD's programs was discussed in the context of a three-legged stool: theory, experiments, and computation, for both the protection and the lethality thrust areas. The 2009 review presentations clearly described the diverse challenges of WMRD as it strives to address near-term ballistic protection to counteract the improvised explosive device (IED) threats facing U.S. troops overseas while still striving to support ongoing R&D and also to reinvigorate longer-term materials R&D. This balanced approach is appropriate: addressing first and foremost the pressing deliverables to support warfighters in the field while continuing to support and grow the fundamental and applied R&D to support the warfighter in conflicts of the future. Clearly the transition of focus within ARL from the Future Combat Systems (FCS) to the Ground Combat Vehicle (GCV) program scope has forced some changes in course within WMRD in the protection area. Complex and shifting requirements issues drive this transition, and WMRD has been commendably flexible in adapting to these changes in focus and scope within its armor protection R&D thrust.

WMRD's overview of its lethality portfolio, presented to the panel in 2010, emphasized the importance of warfighter outcomes (WFOs) in maintaining adversary overmatch, minimizing collateral damage, and providing non-line-of-sight scalable lethality. The breadth of the force application mission was outlined: it spans soldier ground tactics, aviation, fire support and non-line-of-sight, networked systems, scalable effects from nonlethal to lethal—all the while maintaining overmatch.

The high-level emphasis on tuning effects to targets as the focus moves from structures to individuals was detailed for the panel; WMRD also described how this changing emphasis demands variable-scalable lethality. The expressed goal of the lethality program is the right lethality at the right time and in the right place without putting the warfighter in harm's way. The described concept of an armed wingman, an armed robotic entity that separates the warfighter from the energetics and gun mechanisms, is very forward thinking and innovative.

WMRD incorporated the results of discussions with panel members during the 2009 review into its 2010 program in such significant examples as the following: continued emphasis on multiscale modeling and bridging scales, focus on numeric and physics issues in modeling, emphasis on differential verification and validation (V&V), and work on developing a suite of standard validation metrics for the computer codes and simulations.

The previous ARLTAB report[1] suggested that WMRD had not appeared to be striking an appropriate balance between experiment and computational efforts, with too little emphasis on computational and modeling areas. During the 2009-2010 reviews, the balance was found to have improved considerably.

The degree of integration of modeling and simulation with testing and evaluation (T&E) has increased substantially over the past 2 years. Significant progress was evident in the extent to which a balanced view of both modeling and experimental verification was included in most topics; this more effective integration is very positive and should be encouraged. In contrast to previous reviews, for the projects reviewed in 2009-2010 computations were more intimately connected to the research effort—a positive and noteworthy change. There was also greater recognition of the need for V&V. Modeling at different length scales is important, and WMRD evinced positive signs in this area in both the protec-

[1]National Research Council. 2009. *2007-2008 Assessment of the Army Research Laboratory.* Washington, D.C.: The National Academies Press.

tion and the lethality arena. WMRD should conduct more end-to-end simulations (involving simulation of entire processes) and simulations as a function of resolution and timescales; these are challenging problems.

In both the protection and the lethality thrusts, WMRD also presented an enhanced recognition of the systems approach to problem definition and an increased ability to think outside traditional “boxes.” This has clearly led to new realizations of the factors limiting performance and new approaches to addressing old problems. The integration of the protection and lethality R&D thrusts with warfighter tactics, techniques, and procedures (TTPs) is also very proactive, and WMRD is encouraged to continue this emphasis.

WMRD and ARL have restarted a basic energetics synthesis program. This is an exciting and important reinvestment for the entire country, including the Department of Defense (DoD) and national defense programs. ARL’s visionary stance and investment in the future are commendable.

## ACCOMPLISHMENTS AND ADVANCEMENTS

### Protection and Survivability

#### Lightweight Materials for Armor

As a program of alloy development, the Al-2139 is an outstanding example of alloy development aimed at a specific application. WMRD deserves credit for articulating the role of silver (Ag) in the evolution of 2139’s microstructure and the strengthening that results from this microstructure. However, in its current state, the program does not quite rise to the level of materials by design, although there is a good basis here to evolve the program to one of microstructural design and possibly one of materials design. Toward this end, the investigators will need to adopt broader objectives. Rather than rationalizing the origin of measured properties, a more fundamental question must be addressed—namely, what is it about (the atomic structure of) Ag, as opposed to, say, copper (Cu), or gold (Au), that leads to the remarkable properties of this alloy? An answer to this question would allow one to identify other alloying elements, and possibly alloy systems, that might share or surpass the strength of Al-2139.

Trimodal aluminum (Al) was another thrust in the use of Al for protection. This technical thrust area has the potential to increase the strength of Al alloys by up to 75 percent while maintaining good ductility. This is an extraordinary engineering goal and generally would not be believable if the concept had not been demonstrated in a pilot program. The problem over the past 2 years has been to reproduce these outstanding results. It is claimed that the product has been replicated over the past few months. This project evolved from decades of WMRD research into improved Al alloys for armor applications. After successfully producing an ultrafine-grain-sized Al with poor ductility, the investigators used a rule-of-mixtures empirical approach to improve ductility while sacrificing strength. Very surprisingly, they produced a product with both very exceptional strength and good ductility. This material has the potential to reduce the weight of aluminum armor by a factor of two! For the past 2 years, the principal effort was the reproduction of these exceptional results. This effort has led to a better understanding of mechanisms for obtaining higher-strength Al alloys. The composition is far from optimized, but if the strength and ductility have truly been reproduced (which is not yet fully demonstrated), this work has the potential to transform the use of Al for the needs of the Army, Navy, and Air Force as well as civilian aerospace needs. If reproducibility can be demonstrated, this work should receive DoD-wide expansion through the Army Research Office (ARO), the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR), and the Defense Advanced Research Projects Agency (DARPA). This work has the potential to open the pathways for ultrahigh-strength Al as the investigation of martensite and bainite did for steel 80 years ago.

The magnesium (Mg) alloy and process development program within WMRD is clearly a positive approach to examining lighter metals and alloys for structural and protective components in a systems-based approach to armor protection. Mg is lower density but lacks ductility and strength compared to structural steel and is subject to corrosion under certain operational regimes. The use of Mg as part of a systems approach to armor protection therefore seems warranted rather than its use as a monolithic armor. WMRD is to be commended for examining the utilization of Mg and for its follow-through in developing an armor specification for AZ31 magnesium.

## Brittle Materials and Related Technologies for Armor

The ceramic armor materials efforts within WMRD presented for the panel details of the armor concepts under development, particularly in the areas of effective plasticity and multiscale modeling. This presentation detailed the overall context to the work being done in ceramics and transparent materials. Two topics were discussed at greater length:

1. A new project attempting to apply modeling at different length scales (quantum through continuum) to describe the fracture behavior of AlON, combined with some experimental verification at each length scale. The intention is to move from AlON to SiC or $B_4C$ if this project is successful. Although it appears too early to judge the success of this program, the attempt to connect these efforts is laudable.
2. An attempt to use the optical response to ballistic impact in AlON and other transparent materials to understand stress, strain, and defects ahead of the actual fracture front, particularly the phenomenon described as "effective plasticity."

Numerous references were made by the panel to the lack of definitive success criteria, which makes it hard to know what properties or structures should be optimized. (For example, what are the desired fragmentation size distributions for ceramic armor? Also, what is the desired mixture of static and dynamic failure prevention in ceramic armor?) Without crisp success criteria, it remains difficult to understand the real goals of the substantial modeling and experimental efforts that are underway, or how they will be leveraged by the more applied engineering groups.

Accomplishing the implementation of ceramics and other brittle materials in protection systems requires the ability to do the following: (1) find a quantitative way to correlate hardness and ballistics results and nondestructive evaluation (NDE) measures of ceramic-tile quality; (2) provide tools for in-line manufacturing quality control as well as for field assessment of accidentally damaged tiles; and (3) predict their performance, in particular their fracture response, through predictive models. The use of NDE techniques has shortened the laboratory's experimental cycle for ceramic armor evaluation. Preliminary correlations developed between NDE performance of ceramic tiles under ballistic testing have established that the technique can detect defects during the manufacturing process, and WMRD is working on improving the implementation of the technique for manufacturing and field use. The ability to ensure ceramic-tile performance in an armor assembly is essential to the ARL mission, and this work seems to be a good approach to a problem that no one else will solve for the Army.

WMRD's focus on dynamic failure is centered on experimental observation of crack tip propagation and bifurcation, the creation of appropriate constitutive models, and the implementation and validation of such models through computations employing the finite element method. This effort was described as part of a plan to develop a multiscale modeling capability; a number of collaborators are assisting in that larger effort. WMRD did describe having developed two failure-capable finite element models (FEMs)—Ortiz's cohesive zone model and Belyschko's xFEM model—both in two dimensions. WMRD has also begun experimental measurement of crack propagation and plans to employ techniques such as Rosakis' coherent gradient scattering technique in future work to validate the models. The program described is an important one, being central to Army goals of survivability and lethality; the specific continuum computational objectives are appropriate. The challenge of developing a physics-based fracture model that can be trusted (in the usual verify and validate sense) is a significant one that has occupied the careers of many theoreticians and experimentalists at the Department of Energy (DOE) laboratories. ARL's level of commitment to this important area should be increased as soon as possible.

## Structural Composites for Armor Applications

Composite sandwich armor panels as structural units constitute one area of ARL's composite program. The main system examined consists of a woven composite support backplate, ceramic hexagonal bricks as core, and a composite faceplate. Complementary numerical models were developed, but to date they appear to deal with mainly elastic behavior, with the tracking of evolution of delamination ongoing. Overall, this is a good effort that is clearly required to meet Army programmatic needs. The beam experiments performed are a good start, but tests under quasi-static and impact loads on complete panels must follow as soon as practical. Questions include these: Will the panel maintain structural integrity after first impact? After multiple impacts? What is the effect of blast loading on the panels? How does the panel degrade due to the vibration of the vehicle? What NDE methods will be used to evaluate panels in service? What criteria will be used to render panels nonoperational?

The sandwich system being examined currently appears to be a transitional concept for WMRD. New concepts that involve peripheral support of ceramic bricks with specially woven fiber composites appear to be coming onboard in the near future. The same type of effort will have to be expended for such panels. Here, the governing mechanisms will probably be different, governed by nonlinear behavior and progressive damage of the fibrous composite support structure.

WMRD's research to develop woven ballistic fabric models, and the use of these models to optimize the design and performance of woven ballistic fabrics for use in personnel armor and as backing materials and shock isolation systems or ceramic laminate armors, show strong promise and growth. This is a combined theoretical and experimental research project that has a complementary manufacturing technology program. The models being developed in this research are being used to address what weave geometry the manufacturers should make for each application of interest. The research appears to have a very solid underpinning, and there is a clear need for such models, because a large number of parameters can be varied in a three-dimensional woven fabric, and there is a need to be able to optimize ballistic performance for a given armor weight.

The related technical challenges appear to be in the areas of textile modeling and three-dimensional weaving. This research thrust is being conducted by a team that includes WMRD, several universities, and U.S. industry. Three levels of materials models are being pursued: filament-level fabric models, yarn-level composite models, and layer-level composite models. Experimental fabric impact testing has shown some differences between the measured and predicted displacement that is thought to be due to energy loss caused by fiber transverse plastic deformation, friction, and/or a progressive failure of the material.

The yarn-based models being developed in this research are currently being integrated in LS-DYNA, and this code is being used to conduct three-dimensional composite material modeling and ballistic simulations. Although the research is still underway, it is already delivering results that are being used to guide the development of encapsulated ceramic laminate armors that include three-dimensional woven fabrics. This research is producing valuable results that are expected to contribute to the design of higher-performance encapsulated ceramic laminate armors for defeating a range of threats.

### Armor Protective Systems to Support Current Operations

Armor has clearly evolved in various ways over the years as the threats have also evolved. In particular, IEDs are placing new demands on armor. Advances in materials and computational tools have made possible new approaches to address passive armor protection. WMRD highlighted a number of armor technologies and designs that were quickly developed and applied to a variety of combat vehicles used to support current U.S. operations in Iraq and Afghanistan. The armor work highlighted by WMRD clearly showed the value of ballistic protection technology and development capabilities to the Army. The results and accomplishments shown were very impressive and clearly demonstrate ARL's preeminent position in the United States in armor development.

The approaches taken are most often empirical and often have somewhat of a trial-and-error nature, with an increasing level of physically based modeling and simulation clearly being used. WMRD's approach to solving these short-term problems is sound in that it brings modern protection techniques to armor. A continued weakness of this approach, although clearly understandable given the needs to respond rapidly to U.S. warfighters' needs, is the modeling effort, which should continue to strive to build in more and more robust physics and be resolved numerically.

WMRD and ARL management should consider whether ballistic protection support to current operations should continue to be focused within WMRD in the longer term or whether the responsibility for this type of support work should be transitioned to the Tank Automotive Research, Development, and Engineering Center (TARDEC). Although WMRD has demonstrated that it can do this type of support work and do it extremely well, it is not clear that this is the best use of ARL scientific resources, because many of these same researchers could be used to plan and conduct longer-range, high-payoff armor research initiatives that could potentially lead to more effective ways to defeat future threats.

## Lethality

### Strategic Vision

The WMRD Lethality Division has established a lethality strategic vision that serves as a motivator and focal point for all WMRD lethality science and technology efforts. The lethality S&T program has undergone a major restructuring during the past 3 or 4 years, and approximately 30 percent of the program represents new starts aimed at addressing some of the most important perceived deficiencies of the program. The lethality S&T program is currently focused on five research areas: energetics materials and propulsion, affordable precision munitions, projectiles and multifunctional warheads, materials and manufacturing science for lethality, and advanced weapon concepts. The lethality strategic vision addresses a number of user-identified deficiencies arising from current operations in Iraq and Afghanistan, and WMRD pointed out some of the current important lethality deficiencies and user needs in the current warfighting environment. Consideration of user-identified deficiencies has led the WMRD staff to identify new technology opportunities that may offer a way to fill some of these needs. The vision appears to be broad enough that it should be fairly easy for all staff members to see how their individual efforts can support the overall program; however, it appears that some of the newer staff members do not yet see how their work fits into the bigger picture.

### Energetics Research and Development

The Energetic Materials and Propulsion Program is broadly focused on developing new approaches to the storage and release of chemical energy, with the goal of enabling the next generation of munitions and propulsion systems. This focus is mission-appropriate and offers the potential for high payoff for the Army and DoD.

As described, the program is reliant on the development of a fundamental scientific understanding of the principles underlying the storage and release of chemical energy. Because energy release, in particular, is poorly understood owing to a complexity that involves multiple length scales and timescales, it is recognized that, to be successful, the program must integrate modeling and experiment across these same length scales and timescales. The most prominent effort in this area is the 6-year Multiscale Reactive Modeling of Insensitive Munitions project, which will develop modeling capabilities at the atomic scale (modeling chemical decomposition), the mesostructural scale (modeling dislocation dynamics and single crystal plasticity), and the microstructural scale (modeling polycrystalline and continuum response). The models at each level are to be verified experimentally.

Although the project is making good progress at the atomic level—for example, using quantum chemical methods to cull the list of potential high-energy systems before attempting synthesis and to characterize reaction paths and rate expressions relevant to liquid rocket propellants—there was little indication of comparable progress at other length scales. This is not surprising, as the multilength-scale part of the project is extremely ambitious and unlikely to be realized in full over the project's lifetime and with the current funding level. However, the objectives are laudable even if scaled back, and given sufficient time it should produce dramatic payoffs for DoD.

As presented, the energetics material modeling program appears to emphasize quantum chemical modeling and experimental investigation heavily, and verification appears to recieve less emphasis. The energetics material modeling effort should be focused on a few challenging problems selected from appropriate length scales. In identifying these, both the resultant modeling capabilities and experiments needed for their verification should be articulated upfront. More attention should be directed toward maturing models to provide useful design information. For example, can quantum chemical methods be employed not only to identify potential high-energy molecules but also to develop a strategy by which they may be synthesized?

The synthesis and modeling of energetics are clearly important in the area of insensitive munitions. Although WMRD explained to the panel that there are no insensitive explosives, only insensitive munitions (IM), the goal is for munitions that are safer for those deploying them. The munitions must survive certain insults: impact by bullet, fragment, or shaped-charge jet; conditions of slow or fast cook-off (in fire); and nearby detonations (sympathetic detonation). The ARL approach is not novel, but it is likely to achieve the desired result in the allotted time. All of the services attempt to achieve IM by a combination of new materials and new casings. The general approach with casings is to have pressure relief of sorts during fire threat so that the munition breaks open and leaks or burns but does not detonate. For the most part, the new materials discussed are not really new compounds but new formulations: high bulk density nitroguanidine (NTO) and dinitroaniline as the melt-cast replacement for TNT; or eutectics of nitrate salts (diethylenetriamine trinitrate, ethylene diamine dinitrate with nitroguanidine and methylnitroguanidine—DEMN). The ionic liquids are relatively new; the munitions group at Edwards Air Force Base has been studying them for over a decade. These comments are not meant to fault the present program at WMRD; it is a daunting problem, and a solution is wanted now. No doubt the modeling program examining properties and the synthesis program creating new materials will, in the long term, provide better answers than those available today.

### Energetics Synthesis and Disruptive Energetics

WMRD is a leader in the field of advanced energetics materials. The DOE nuclear community and other branches of DoD have had active programs in this area in the past, but most have scaled back or eliminated such efforts. WMRD personnel indicated that the Office of the Secretary of Defense (OSD) has recognized and supported ARL's efforts in this area.

WMRD is, commendably, encouraging early-career chemists to pursue the synthesis of new molecules for explosives. ARL should send its synthetic chemists to spend time at the Los Alamos or the Livermore National Laboratory with the current U.S. explosives synthesis chemists. In addition, at least three outstanding chemists who spent their careers making explosive compounds are now retired and may be available for consultation.

### Theoretical Predictions and Modeling of Energetics Material Properties

The goal of the theoretical energetics program is to predict the physiochemical properties of energetics materials using ab initio methods (density functional theory [DFT]) and molecular dynamics, which will build on the results of the DFT calculations to construct appropriate force fields. As well as providing information for force field development, the DFT calculations are being explored for their usefulness in predicting heats of formation and the crystal structure of energetic molecules.

The use of DFT and other quantum mechanical calculations to determine heats of formation and crystal structures of potential high-energy materials will likely be successful. Verifying the calculations against the structures of known systems is appropriate and will establish an error range (much like an experimental error) on the calculations. The use of force field models to extract information about phenomena such as shock sensitivity is much more ambitious and is unlikely to see near-term results.

Although the overall thrust of the program was detailed for the panel, the objectives of the force field modeling were not clearly stated. Are the force fields to be used to model the shock wave in a decomposing energetics material, or are the goals more reasonable—for example, to predict mesostructure parameters? Also, there was no evidence of a carefully constructed experimental program to look at energetics materials beyond the atomic level. WMRD should clearly articulate the goals for the force field modeling of energetics and provide an experimental method to verify the results. An appropriate effort might be to predict the elastic constants of a crystal of energetics material and when successful to study the effects of shear on molecular conformation.

### Guidance, Navigation, and Control of Flight Bodies

The experimental results and simulations used to analyze the path of projectiles stabilized by gyroscopic control were very impressive. The analysis was well conceived, and it provided clear evidence for the value of the proposed control mechanism (taking advantage of a control spinner from the rear). A by-product of this work was an analysis of the flight profiles of retrofitted projectiles. The simulations did an excellent job of recovering the profiles as affected by the use of canards at the front end. They also showed clearly that this control mechanism could be expected to provide weak control of the trajectories. This project was successful on several fronts: WMRD designed a reduced system of ordinary differential equations (ODEs) that is capable of reproducing the controlled trajectories well and hence may lend itself better to onboard calculation. The design that followed provided the use of a spinner to stabilize and control projectile trajectories. WMRD provided a clear analysis (by customer request) of the flight dynamics of a retrofitted projectile and an explanation of why it does not lend itself to adequate control. An opportunity in this project area lies in the design of retrofits that would provide the requisite guidance, navigation, and control constrained by the requirement that only the nose cone can be modified. WMRD's experimental and modeling efforts in this area are considered to represent the state of the art in DoD and are to be commended.

Another flight-control project considered the modeling of magnetic fields, nominally those of Earth, but as observed inside a spinning metal body in the presence of pulsed electrical circuitry, as a path to utilizing this approach to flight control. The approach was described as hierarchical—analytical solutions for simple geometries validated a finite element analysis (FEA), and the FEA technique was then applied to more complex configurations. A Monte Carlo strategy was used to assess acceptable tolerances of hypothetical manufacturing processes. Overall, the approach was well founded and the results impressive. One area of note was the discussion of very small deviations between the FEA calculations and a set of experimental measurements. The WMRD program plan suggested that with more careful experimentation, these errors would diminish. This is certainly possible, but it is also possible that the numerical calculations were in error. Elementary grid refinement studies that might support the belief in the FEA computation as being more reliable were not presented. An awareness of the limitations of the numerical techniques appeared underappreciated by WMRD; the issue should be more closely examined.

### Gun and Rocket Propulsion Research and Development

The reaction mechanisms employed for gun and rocket propulsion modeling (outside of ARL) are highly simplified constructs with empirically adjusted parameters, limiting their applicability as well as their ability to accurately simulate highly transient events such as thrust and throttling. The purpose of this research is to reduce the number of empirical parameters by using first-principle methods to determine the mechanism for propellant reactions, which in turn will be used to simulate combustion-chamber dynamics. More than a hundred mechanisms were identified using first principles. This large number creates a kinetic complexity so vast that it is difficult to believe the combustion simulations that follow. To provide confidence in the calculations, WMRD should model a simple starter system (one with a few reactions and less complex kinetics) that can be interrogated experimentally. Next, it should demonstrate that the model is consistent with the experimental results before proceeding to more complex problems.

Further, WMRD is applying its expertise in computational chemistry to develop a model for the burning of a specific propellant, which can in turn be used as the constitutive model within a continuum code to compute the performance characteristics of candidate rocket combustion-chamber designs. The propellant has many components, and the possible reactions number around five hundred. Quantum methods are used to compute the thermodynamic and kinetic constants that enter into the rate equations that govern the propellant burn. This is a huge task in its own right, involving enormous amounts of computational time. Selected individual reaction rates have been validated against experimental data. To scale the description to the level needed for chamber design and assessment, the number of rate equations needs to be significantly reduced by a systematic process that eliminates the least important. This is an essential step in the multiscaling of this system, because otherwise the number of rate equations would be far too many to employ in the macroscopic computational model in which each spatial point is governed by its own system of rate equations.

WMRD has invested heavily in developing computational fluid dynamics (CFD) models for the design and analysis of hypergolic liquid bipropellant rocket engines with selectable thrust capabilities as well as hybrid rocket engines (i.e., solid fuel with hypergolic liquid oxidizer) in FY 2010 and FY 2011. In FY 2011, detailed chemical kinetics mechanisms for these fuels will be coupled with the ARL CFD model and validated using test-stand data. Subsequently, the model will be used in FY 2011 to complete the design testing of the Army's hybrid tactical missile engine at the Aviation and Missile Research, Development and Engineering Center, and in FY 2012 it will be used to aid in the flight test of a hypergolic liquid bipropellant rocket engine for tactical-battlefield-class missile platforms. If successful, this project will provide an excellent demonstration of the power of multiscale modeling. Moreover, the general approach should have broad applicability. WMRD is to be commended for this effort.

### Multiphase Blast

WMRD presented experimental results and its programmatic thrust on blasts from TNT-Al mixtures, with the Al phase having different textures: spherical or granular. The measurements included pyrometry, front velocity (with a framing camera), pressure, and gas composition. The goal was the creation of a data set to inform future computer modeling efforts, which might subsequently be used to optimize so-called scalability of explosions. The experiments themselves were appropriate, though conducted without consultation with modelers. Consequently, one might wonder whether the observed quantities adequately test the computational approach, or provide necessary constitutive properties. This dialogue should occur as the project evolves so that a more complete understanding of the operative physics can be achieved.

Thereafter, given a specific blast, as specified by the explosive pressure pulse released in a room for example, the question addressed is: What is the pressure pulse experienced by an individual's chest cavity when that person is standing at different locations in the room? The chest has been modeled by a one-dimensional spring-mass-dashpot system with inputs from biomechanical data. The objective is to understand the likelihood that the individual can survive the blast, or the contrary, and it is part of WMRD's broader effort to develop scalable weapons with limited collateral damage. The simulations can account for the shape of the blast pulse, and this ties into the project on multiphase blast, because the aim of that project is to produce blast pulses of different shapes. The project could benefit from additional inputs of two types. First, there is work that significantly addresses the pressure pulse interaction considered here and which would probably provide analytical results.[2] Second, greater collaboration with a biomechanics expert on blast damage to living beings would seem to be called for, given the objectives of the project. Although probably important to questions related to scalability, the project is not particularly ambitious.

### Precision Simulation Environment Initiative

The precision simulation environment initiative within WMRD grew from internal capabilities of the Lethality Division and was stimulated by the Very Affordable Precision Projectile (VAPP) Program. Essentially, a collection of models (based on physics, empirical data, and statistics) has been integrated to allow for the early assessment of VAPP prototypes during both initial development and refinement prior to demonstration. The simulation environment also supports a complete hardware loop that includes an initial loading of mission parameters into the warhead, in-flight telemetry and real-time stimulation of onboard actuators, and performance data acquisition and analysis. This simulation environment has contributed to the success of the VAPP Program. The precision simulation environment is a useful application of integrated models (with different bases) coupled with a hardware interface to test prototypes that provides a complete simulation of a family of new munitions. Such an approach is recommended for future munitions development, with the caveat that the simulation environment be made as robust

[2]N. Kambouchev, L. Noels, and R. Radovitzky. "Compressibility Effects on Fluid-Structure Interactions and Their Implications on the Blast Loading of Structures." *Journal of Applied Physics* 100(6):063519, 2006.

and accessible as possible, with the least dependency on a specific individual for its routine use and adaptation to new systems.

### Multiscale Modeling of Lethality Materials

WMRD has applied reasonable, state-of-the-art density functional theory methods for gaining an understanding of the structure of the grain-boundary interface as a function of dopants. (The dopants arise from the sintering aids employed in creating the $Si_3N_4$ ceramics that underlie the tiled materials.) The primary result so far is the prediction of the likely positions in which dopants are to be found on the surface, assuming uniform models for the adjoining ceramic. These distances and several metrics for related clusters have been properly validated by experiments. There are two schools of thought as to how this research may proceed. According to one school, the future stages of this work will require a better understanding of the molecular dynamics at the interface, their reactivity, and detailed interaction with the adjoining ceramic. This will require the use of new methods, ranging from reactive force fields (e.g., REAXFF), to the use of molecular dynamics codes (e.g., LAMMPS), to other methods to explore rare events. The other school conjectures that cohesive enhancement results from local interactions that extend only to first- and perhaps second-neighbor interactions around the impurity site. In such a case, one may be able to identify cohesive enhancers as elements with a set of identifiable atomic properties, such as d electron count. Thus, a detailed simulation of dynamic properties is unnecessary. It is notable that WMRD is pursuing research in this area with an eye toward both possibilities. Regardless of which line of thought is borne out, ARL would likely benefit from interaction and collaboration with other groups studying interfacial cohesion and from a more thorough review of the literature.

### Warheads and Projectiles—Ongoing R&D and New Thrusts

WMRD's S&T program in warheads and projectiles has changed over the past decade, and in particular the last few years, moving from a strong focus on tank-on-tank engagements to the spectrum of problems faced by small units fighting distributed engagements, especially in urban environments. These distributed engagements take place in military operations both in urban terrain and in more open environments. A few examples from the WMRD portfolio, provided below, illustrate this point, as well as showing ARL's lead and excellence in addressing challenges to the Army posed by very quickly evolving threats and therefore evolving needs for warheads with tailored performance. The focus of the warheads and projectiles S&T program has been shifted to scalable/adaptable effects, weapon effects in urban operations, next-generation kinetic energy projectiles, and increasing soldier lethality. The capability to tailor weapon effectiveness through various approaches (e.g., designed grooves, dual-purpose energetics) is interesting and offers the possibility of reducing collateral damage in complex urban environments. Working on various approaches to scale and adapt warhead performance using careful experimentation and computational tools is encouraged and could have high potential payoff in the future.

**M855A1 Round** The WMRD-led S&T effort that resulted in the type classification of the M855A1 round provides an example that shows how the S&T program has changed. The M855A1 solves a user need for an improved 5.56 mm round that can deliver more consistent antipersonnel lethality in a variety of operational scenarios and that can also deliver adequate performance against light armor and be environmentally friendly (green). The WMRD effort focused on gaining a detailed understanding of the causes of the performance issues associated with the current M855 round from an integrated viewpoint involving aeroballistic, terminal ballistic, and personnel incapacitation concerns. This improved understanding permitted a WMRD-led team to identify a new design concept that could provide improved performance and also be more environmentally friendly than the currently fielded M855 round is. The WMRD warheads and projectiles S&T program also includes, among other efforts, research in areas such as a multipurpose artillery round that can produce selectable energy output, extensible rods and/or segmented penetrators, and advanced tungsten alloy penetrator materials that can be used in place of depleted uranium with no loss of performance. The warheads and projectiles S&T program appears to be focused on appropriate objectives that, if achieved, will make a difference to warfighters.

**Affordable Precision Munitions** The Army has an urgent operational need for affordable, precision, indirect-fire munitions (artillery and mortars) that cause low collateral damage. The focus of the current Army efforts has been on precision 105 mm and 155 mm artillery munitions and 120 mm mortar munitions. The Army has fielded Excaliber, a 155 mm precision artillery munition, but this munition has a very high unit cost (approximately $60,000 or more) that limits its availability. The Army currently has a need to be able to retrofit the existing large stockpile of 105 mm and 155 mm artillery projectiles at low cost by adding relatively inexpensive guidance kits to current "dumb" projectiles. The kits that are currently in development, however, do not provide as much accuracy as the user desires at all ranges of interest. The WMRD affordable precision munitions technology program attempts to address the user's need for more affordable precision munitions by developing and demonstrating new technologies that go beyond those considered by other researchers. The WMRD program focuses on several areas: reduced-state guidance, navigation, and control; unsteady aerodynamics; structural dynamics; and precision munitions technology demonstrations, including guide-to-hit tests. The precision munitions technologies that are being pursued in the WMRD program have been selected in order to break the current high-cost paradigm. Both the WMRD initiative and its approach are appropriate: the technical approach being pursued features a combination of analytical and computer modeling, laboratory/bench experiments, and full-scale field testing, including guide-to-hit tests. WMRD has made impressive progress in this area and should continue to push the state of the art. This is a challenging technical problem, but there may be a near-term opportunity for WMRD to make a real difference to the Army by providing more cost-effective technologies for low-cost precision munitions.

**Scalable Binary Annular Munition** Scalable Binary Annular Munition (SBAM) is aimed at conceptualizing and demonstrating a novel, explosive-based munition that can provide several (at least two) selectable energy outputs. This novel explosive containment and initiation concept would form the basis for a lethal, scalable munition that can tailor the energy output (fragment speed and mass, as well as blast effects) delivered to the target. Proof-of-concept testing has been conducted, demonstrating that two different output modes can be achieved. At this point, it is too early to tell whether these two particular output modes will provide useful target effects. Additional work will be needed to quantify the effects that can be achieved, the target types that can be addressed, and the potential impact on collateral damage.

### Materials and Manufacturing Science for Lethality

WMRD should continue investments in developing materials and processes for new warheads and projectiles and for increased lethality in support of the warfighter. Specific thrust areas include the following:

- *Depleted Uranium Replacement Program (Nanocrystalline Tungsten Particulate Processing):* WMRD's thrust is aimed at achieving an effective replacement for the depleted uranium (DU) used in kinetic energy penetrators by showing that fully dense, nanostructured tungsten (W) will exhibit the suitable ballistic launch properties and adiabatic shearing at impact that give DU its superior ballistic performance. To replace DU, a combination of high density, dynamic shear localization, engineering properties, and a viable manufacturing route is needed. WMRD is pursuing two approaches: equal channel angular extrusion (ECAE) and a bottom-up approach by means of powder-processing techniques starting with nanoscale tungsten. Sintering curves were obtained that showed the time-temperature-densification relationships for milled tungsten powders. The researchers have identified the most promising materials and processing routes for continued development. This information will serve as a guide to the optimization of all the necessary properties, after which small-caliber gun tests will begin. The trial-and-error work is somewhat Edisonian, but the required properties have been well identified, and the parametric work shows how the properties can be changed. This gives the project a high probability of success in the near term. The calculations by Johns Hopkins University on the shear-banding of the bimodal mixtures is interesting. More theory and simulation could help guide the approaches taken by WMRD.

- *Equal Channel Angular Extrusion as an Alternate Processing Route for Penetrators:* ECAE is a process for forming a rod of any shape by taking it through a 90º bend in the process, shearing it severely. The WMRD research group has developed an ECAE facility consisting of a custom device that operates in a large-capacity press. The facility is used to deform W extruded rods at elevated temperature (600ºC to 1200ºC) intended as armor penetrators replacing depleted uranium. Commercially available W rods have relatively large (approximately 200 mm) grains along their axis and associated yielding anisotropies. These features have been shown to result in splitting axial cracks in Hopkinson bar experiments that are debilitating in high-penetration projectiles designed with W. Overall, the ECAE capability constitutes a strength area for WMRD. The application of the method to W is worthwhile, and the study of failure modes is useful to the Army's efforts to replace DU with W.
- *Gun Liner Emplacement by Elastomeric Materials (GLEEM) Processing:* WMRD is examining GLEEM processing for lining and/or autofrettaging a gun barrel to enhance its service life. The initial demonstration has been with a CoCr alloy, smooth-bore tube formed over a mandrel. Chromium (Cr) in an alloy is acceptable, but not in plating, because of Cr toxicity issues. The tube is slipped inside the gun barrel, and then a set of stacked elastomer plugs is inserted. One plug at a time is tamped down with a stainless steel rod, to impart stress onto the side-walls of the tube, exceeding the deformation stress of both the tube and the interior surface of the gun barrel itself. WMRD researchers have measured the bond strength achieved at about 3,000 psi, which is comparable to or in excess of current liners inserted using shrink-fit operations. WMRD's next step will be to send the barrel-and-liner to a company to machine the rifle bore and then test it, as well as to work on other materials like Ta-10W (which has increased hot strength). WMRD researchers believe that the major challenge to scaling up will be controlling the friction in the process. This project seems to be very applied engineering with little evidence of systematic research and development or modeling to guide the effort. WMRD should examine whether this development project can be designed to incorporate a more coupled experimental-modeling emphasis.
- *Ceramic Gun Barrel Materials:* Ceramic gun barrels are once more being considered by the Army as an alternative to metal gun barrels. The advantage that ceramics provide is that they can reduce the weight carried by soldiers in the field. Apparently such efforts have some history at ARL, where ceramic tubes with internal rifling were previously designed and fabricated. They were subsequently wrapped with carbon-fiber-epoxy composite layers pre-tensioned so as to place the

ceramic tubes under compression. During the firing of projectiles through such tubes, the pressure levels approached the strength of the ceramic, raising questions about the feasibility of the concept. Recent developments at ARL have shown that the strength and toughness of $Si_3N_4$ and SiAlON ceramics can be significantly increased by the addition of small amounts of rare-earth oxides (strength > 1 GPa, toughness > 10 $MPam^{0.5}$). The improvements have been shown to result from grain boundary modifications that are introduced by the added metals (which segregate at the grain boundaries and couple with $SiO_2$ to create amorphous intergranular films). The improvements are sufficient to make the ceramic barrel scenarios plausible. This project includes the mechanical evaluation of the new ceramics and the development of new barrel-manufacturing efforts, while simultaneously pursuing quantum mechanical and atomistic modeling of the effect of the added metals on the grain boundaries.

Overall, the project has a good balance between basic and applied research. A weakness is the apparently limited projected use of ceramic barrels because of the slow cooling rate of the wrapped ceramic concept. The issue of their resilience to impact also needs to be addressed and remains a significant barrier to scale-up and end use in the field.

## OPPORTUNITIES AND CHALLENGES

The Weapons and Materials Research Directorate is pursuing an appropriate mission that is well suited to its excellence in S&T in the areas of protection and lethality and is serving the short-term tactical needs of the warfighter as well as adhering to an S&T vision to prepare for wars of the future. That said, there remain opportunities and challenges.

During the 2009-2010 review cycle, WMRD continued to demonstrate increased emphasis on coupling experimental and modeling efforts within its programmatic efforts; achieving and maintaining this balance constitute a worthy goal. Neverthless, error convergence in all modeling and simulation efforts should still be pursued and can be improved. In addition, verification and validation, while more obvious in the current review cycle than ever before, should continue to receive attention. More case studies in which the accuracy of the codes is checked against validation experiments should be strongly encouraged by WMRD management.

An increase in the number of new, early-career staff is clearly reinvigorating the staffing in the directorate. This hiring trend should be continued as the path to sustainable excellence in the areas of protection and lethality.

WMRD is making an investment in energetics synthesis, a national asset to support both DoD and DOE programs. WMRD should continue to pursue its building of a core program in this area.

WMRD's control of the intellectual property in the area of precision design projects is an excellent approach to the development of new munitions, because it helps to maintain expertise within DoD through such means as patents and publications. Holding the intellectual property within the Army and within DoD should be encouraged across an increasing number of technical S&T areas. The low-cost precision munition work is a strong, exemplary success story.

Much of WMRD's energetics materials modeling program appears to emphasize quantum chemical modeling and experimental investigation heavily; verification appears to receive less emphasis. The energetics materials modeling effort should be focused on a few challenging problems selected from appropriate length scales. In identifying these, both the resultant modeling capabilities and experiments needed for their verification should be articulated upfront. More attention should be directed toward maturing models to provide useful design information. For example, can quantum chemical methods be employed not only to identify potential high-energy molecules but also to develop a strategy by which they may be synthesized?

The WMRD program in advanced weapons concepts is designed to identify projects that have high risk and high payoff for the Army. Innovative ideas are sought from WMRD researchers and leadership that bear on the mission of the Lethality Division and meet immediate or perceived future needs of the Army. The number of proposals considered has grown from 4 in FY 2009, to 11 in FY 2010, to 31 for FY 2011, demonstrating the success in stimulating idea generation within the division. Interaction with the warfighter has occurred in evaluating the utility of some proposals. Input has also been sought from the U.S. Army Training and Doctrine Command and other Army customers.

Based on the success of this program in advanced weapons concepts in the Lethality Division, it appears that similar programs should be launched in other areas within WMRD's portfolio, so long as the criteria for funding are such that high-risk, high-payoff projects are likely to be funded over those that are deemed to be more conventional and that program funding is not used to augment or supplant standard funding mechanisms. Researchers in the Lethality Division should be encouraged to identify customer proponents to enhance the likelihood that standard project funding follows closely on the success of the initial project.

WMRD should consider conducting a comprehensive trade-off study for the SBAM munition (if this has not already been done) and using the results of such a study to help guide and optimize the munition design concept.

## OVERALL TECHNICAL QUALITY OF THE WORK

The Weapons and Materials Research Directorate continues to conduct science and technology of very wide breadth and great depth, protecting warfighters and providing them with robust lethal instruments to carry out their mission objectives.

The fact that even in time of war in Iraq and Afghanistan when short-term tactical problems such as protecting the warfighter from IEDs have been given to WMRD, the directorate has maintained an excellent series of S&T programs to invest in science and engineering programs for meeting future Army needs. WMRD's integrated expertise in warfighter protection and the development of lethal devices, systems, and platforms to support the warfighter remain excellent—a shining example of balancing fundamental science and engineering with the short-term tactical needs of the Army and DoD.

High-quality research is being carried out in almost all WMRD areas of interest: materials development and characterization thrusts, model development, and simulation. The WMRD-led S&T effort on the M855A1 round and the affordable precision munitions program are examples of the strong technical expertise embodied in WMRD. WMRD is strongly encouraged to continue its focus on capturing and controlling the intellectual property and modeling and simulation expertise in the protection and lethality areas.

As the path to the development of advanced modeling and simulation tools aimed at predictive capability to support future systems, WMRD is strongly encouraged to continually refine models coupled to systematic validation experiments over a range of scales and to be mindful of quantitative assessment of the margins and uncertainties in their numerics and simulations.

WMRD and ARL have restarted a basic energetics synthesis program. This is a very exciting development and an important reinvestment for the entire country, including DoD and national defense programs in general. ARL's vision and investment in the future are commendable.

# 8

# Crosscutting Overview

## CROSSCUTTING ISSUES

### Cross-Organizational Planning and Management

The Army Research Laboratory Technical Assessment Board (ARLTAB) was asked by the ARL Director to identify technical opportunities that ARL should be pursuing but is not doing at the present time. In some instances, examples of these opportunities are identified and discussed in the directorate-specific chapters in this report. There is, however, one generic response to this charge. It has long been agreed that many of the most exciting breakthroughs in science and technology (S&T) take place at the interfaces between disciplines. To identify and pursue such opportunities, laboratories must create a process, provide incentives and resources, and use evaluation metrics that measure progress. Consider, for example, the broad topic of "robotics and autonomous systems." Most, if not all, ARL directorates have some effort in this area. The ARLTAB panels—one for each of ARL's six directorates—reviewed many individual projects, but the panels came away with no sense of a collective vision across directorates guiding these efforts and encountered relatively few cross-organizational projects jointly managed and jointly monitored by several directorates. Yet this field of robotics and autonomous systems cries out for collaborative efforts that range from design, to materials development and/or selection, to communication, to sensing, to human-machine interfacing.

When this subject was subsequently explored with the ARL Director, it was revealed that a rich, diverse array of such collaborative efforts *does* exist in many technical areas throughout ARL. These efforts were not commonly being briefed in panel reviews, however. To encourage such briefings and the discussions that they would likely engender, ARLTAB recommends that an additional assessment criterion be added to those currently governing the ARLTAB statement of task—one focused on cross-organizational collaborative effort (Appendix C presents the complete set of current assessment criteria). Directorates, responding to such a charge, would be expected to clarify the planning, management, and content of such cross-organizational endeavors. ARLTAB panels would continue to focus on one directorate in each review. Representatives from collaborating directorates might be invited to such cross-organizational briefings, and they might contribute to interactive discussions, but they would not normally be presenting the briefing itself. In addition, ARLTAB encourages ARL to continue to take advantage of the opportunity to use the Board to carry out additional reviews of specific cross-organizational programs as they are being developed and executed. Such reviews would encourage the gap analysis required to address properly the issue of what additional opportunities should be pursued by ARL.

## Deficiencies in the Research Process

In most of the projects reviewed, the research problems and objectives were clearly and adequately defined; investigators showed their awareness of related research in the extramural community and had formed productive collaborations where available. The language-translation work in the Computational and Information Sciences Directorate (CISD) evinced a well-planned movement from speech recognition, to text translation, to the current focus on parsing large volumes of documents. The CISD program in network analysis proceeds according to a clear articulation of project goals and plans. Additional strengths of this program include the support of three new Small Business Innovation Research (SBIR) projects on source selection, a focus on interdisciplinary collaboration, and expanded interactions with the Office of the Secretary of Defense (OSD), the Multidisciplinary University Research Initiative (MURI), Collaborative technology Alliance (CTA) participants, and end users.

In the Sensors and Electron Devices Directorate (SEDD), as a general rule changes are guided by a clearly stated long-term vision for each of the major SEDD mission areas. For example, the vision for the area of extreme energy and power describes an objective to provide the individual soldier with access to two or three augmented energy sources on the mesoscale and microscale, and the vision for the area of heterogeneous electronics highlights intelligent systems built from multiple technologies integrated into clothing, vehicle surfaces, and other stuctures in the warfighter's environment.

The emerging neuroscience group in the Human Research and Engineering Directorate (HRED) has clearly set goals as part of its management of in-house programs and CTA collaborations. In the Survivability and Lethality Analysis Directorate (SLAD), the development of the methodology for achieving an understanding of underbody blast effects is well thought out and combines appropriate physics and necessary codes for assessing damage to vehicles. There is a good understanding of the limitations of the various elements that are interconnected to form the overall methodology. SLAD's Target Interaction Lethality/Vulnerability (TILV) programs demonstrate collaboration efforts with the Weapons and Materials Research Directorate (WMRD) as well as the U.S. Air Force Research Laboratory (AFRL). There was also collaboration in international data-collection efforts using facilities such as the test ranges at Aberdeen Proving Ground, Maryland; facilities at Adelphi, Maryland; and Eglin Air Force Base, Florida, as well as ARL's computational facilities.

The Vehicle Technology Directorate (VTD) has developed a capability concepts approach that allows VTD to connect research projects to specified objectives and to prioritize research and research areas so that work impacting several capability concepts can be moved forward, and research that does not apply to any capability concept might be redirected or stopped. At VTD, some high-quality technical work contributes significantly to the work of the overall technical community. For example, the compressor-tip-injection stall control work that couples experimental data and computational fluid mechanics is state of the art and will enable the industrial design community to improve gas turbine fuel economy and reduce compressor stall. In a similar manner, the windage work in high-speed gear systems is state of the art and promises to improve gearbox efficiency across a wide range of vehicles. The 3,000 to 10,000 shaft horsepower gas turbine (Versatile Affordable Advanced Turbine Engine [VAATE]) Program has well-defined metrics; leverages technology development across the Army, Air Force, Navy, NASA, and industry; and, if successful, will enable several classes of new Army vehicles. In all of these areas, VTD exhibits awareness of and is leveraging a wide range of government, industry, and university research to achieve the needs of the Army.

In most of the projects reviewed during the 2009-2010 period, appropriate scientific and engineering methodologies were applied, and an adequate mix of theory, modeling, and experimentation was in place. An example of CISD work showing good experimental design is a study of how better visualization techniques (i.e., how to cluster for display purposes large amounts of disparate data) aid in reducing the timing of decision making in high-tempo workloads. WMRD's well-coordinated experimental and modeling efforts in the area of guidance, navigation, and control of flight bodies represent the state of the art in the Department of Defense (DoD). WMRD's initiative in affordable precision munitions applies an appropriate technical approach that features a combination of analytical and computer modeling, laboratory/bench experiments, and full-scale field testing, including guide-to-hit tests.

Commonly, but to a lesser extent, verification and validation (V&V) efforts were appropriately applied to lend credibility to the models employed. At CISD there are research areas such as machine translation in which a V&V mind-set has become central to the research process. Also, both the early work in CISD on materials with complex microstructures that are hit with a shock of some kind and the modeling of antimicrobial peptides with bacteria membranes seem focused on a good formulation of their respective problems, with a solid initial approach; these projects have developed good collaborations with leading academic centers, and for at least early work included suitable checks on the potential limits of the models. The CISD Battlefield Environment Division (BED) has for a long time taken care to save the data sets that come out of V&V experiments, and that practice has provided a rich knowledge base for fueling future work.

Despite the strengths exemplified above, sufficient examples of deficiencies in the research process were observed to warrant notice. In some instances, the research problem and objectives were not clearly articulated. In SLAD, the problem context for system-of-systems analysis (SoSA) has not been clearly defined. There is a concern that the direction for the system-of-systems (SoS) framework and philosophy is to develop a platform for analysis and evaluation of survivability, lethality, and vulnerability (SLV) without a specific plan. The details that address the objectives, requirements, and operational level for SoSA model development are lacking. There is need for a concise plan that includes the rationale for the use of SoSA in SLAD, an explanation of how SoSA will contribute to the SLAD mission, and the identification the technical personnel support necessary to sustain the function. This plan needs to define how SoSA tools will be established and implemented, and it also needs to identify one or more specific applications that will prove the worthiness of this tool relative to the SLAD portfolio.

CISD work on managing very large databases was not sufficiently connected to the tactical needs of the Army or to other, related work in the broader intelligence community, and it needs to be put in that context. The project needs to have a clearly stated objective that is consistent with the mission of ARL. CISD work on networking will benefit from a more careful articulation of the key problems being attacked and how the research is being directed to address them. For example, the work reviewed in this cycle tended to divide between strong theory that is not crisply described in terms of its relationship to real Army problems, and work that has a good Army connection but loses the connection with networking.

Within the work in WMRD on theoretical predictions and modeling of energetics material properties, the objectives of the force field modeling were not clearly stated. Are the force fields to be used to model the shock wave in a decomposing energetics material, or are the goals more reasonable—for example, to predict mesostructure parameters? Also, there was no evidence of a carefully constructed experimental program to look at energetics materials beyond the atomic level. WMRD should clearly articulate the goals for force field modeling of energetics and provide an experimental method to verify the results. An appropriate effort might be to predict the elastic constants of a crystal of energetics material and, when successful, study the effects of shear on molecular conformation.

At HRED there is a noteworthy absence of advancement in articulating the content and structure of the social and cognitive network science domain as envisioned in program research; there appears to be no strategic plan or logical narrative guiding the program. HRED's Environment for Auditory Research (EAR) is a world-class auditory facility. However, it remains unclear if there is a utilization plan that will produce world-class results at this facility.

Researchers on several significant projects would benefit from a greater awareness of the research performed by others; that is, the work does not seem to take into account related research that is being conducted elsewhere or does not evince state-of-the-art methods, techniques, or technologies. HRED researchers need to improve their contact with contemporary research in the area of human-robot interaction. HRED researchers seem somewhat isolated from closely related research being done at universities and at other DoD facilities. Contact with this work is important, in part because there are technical advances that can be of use to HRED. More broadly, contact helps shape the research questions that actually serve to advance the field. Additionally, as this research moves into areas that involve traditional studies of human-computer interactions, it is important that HRED personnel learn techniques and methodologies from that area rather than trying to apply methods that they already know are inappropriate for the research problems that they face. Furthermore, it is not at all clear that HRED is positioned appropriately to conduct research in some of the areas in which it is engaged (e.g., cognitive robotics). Although engaging with these problems reveals vision and foresight, it is not clear that the full range of required technical knowledge is present in the HRED staff or that the limited resources applied are adequate to make meaningful progress. Finally, it would be useful to have a centralized mechanism to facilitate information sharing, research review, and discussion across the widely distributed HRED robotics-related researchers. Individuals with limited robotics experience would benefit from interaction with others who have more extensive, ecologically valid robotics evaluation experience. Similarly, in the case of the sensor fusion work in vision at HRED, the project does not seem to evince adequate contact with the very substantial work on this topic that occurs elsewhere in DoD and other domains (e.g., in medical imaging).

At CISD there is potential within the area of network research to accumulate unique, world-class data sets from experimental and/or modeling efforts and to document them in ways that will allow them to be useful both to future ARL efforts and to the larger research and development (R&D) community. WMRD's work in the multiscale modeling of lethality materials would likely benefit from interactions and collaboration with other groups studying interfacial cohesion and from a more thorough review of the literature. ARL's recently initiated program Materials in Extreme Dynamic Environments (MEDE) is a very promising approach to creating a collaborative team to address multiscale modeling to contribute to the achievement of significant Army materials applications.

SLAD has the opportunity to develop additional knowledge and expertise by expanding its awareness of non-Army programs, capabilities, and advanced concepts. For example, SLAD was not aware of an AFRL program called Laser IRCM Flyout Experiment (LIFE) that developed and tested a prototype of a closed-loop infrared countermeasures (IRCM) capability for large, fixed-wing aircraft. This technology could have application for Army platforms and should be considered. All of this information has been openly discussed at conferences and is readily available on the Internet, yet SLAD personnel were not aware of it. SLAD would benefit from becoming more involved in and aware of non-Army electro-optic countermeasure (EOCM) programs and the lessons learned from those programs. Attending conferences is an obvious means of expanding this awareness. SLAD should also seek out information on advanced concepts and roadmaps from its DoD colleagues.

In several cases, a project's researchers would benefit by collaborating with researchers in other fields or at other organizations, extramural and/or within ARL. At CISD, without care in performing human-computer network experiments, the actual value to the Army could be limited. In particular, using just delay and loss measures in the data network models seems limiting, especially in terms of parameters that are relevant to how humans interact with such networks. Better coordination with HRED and the Communications-Electronics Research, Development, and Engineering Center may be able to help with realistic assumptions. CISD should consider introducing Training and Doctrine Command-validated behaviors into research, and interacting with the Joint Experimentation Directorate. In other areas, such as data mining, in which there is no history of internal projects or collaborations with others outside ARL, there is little understanding of other work or awareness of the availability of existing program packages.

In some instances, the scientific approach, plan, or method applied did not seem appropriate, adequate, or clear. At HRED, questions have arisen in the area of statistical analysis and interpretation. In some cases, the analysis did not seem to be correctly performed. In other cases, the distinction between statistical significance and scientific or practical significance was lost. At VTD, testing and field demonstrations of autonomous vehicles and their interaction with terrain and humans are very important. VTD's Fort Indiantown Gap facility is well equipped to conduct this type research; however, some of the results from recent tests of experiments suggest that the design of the tests and analysis of data gathered is a challenge for VTD. VTD personnel should develop expertise in the design and conduct of robotics experiments.

Some projects lack an adequate mix of theory, modeling, and experimentation; and at times insufficient analytic and theoretical research is provided to support models, simulations, and experiments. At WMRD, the Gun Liner Emplacement by Elastomeric Materials (GLEEM) Processing project seems to involve very applied engineering with little evidence of systematic R&D or modeling to guide the effort. WMRD should examine whether this development project can be designed to incorporate a more coupled experimental-modeling emphasis. At VTD, there is a need for the modeling of vehicle systems. The results of good models, such as performance prediction and scalability studies, seemed absent in the many of the VTD projects presented. Research on robotic platforms and air vehicles needs modeling to improve the understanding of performance limits and optimization of platform parameters. Modeling is also critical to system design; good models are the key to insight into the underlying physics, from which meaningful metrics can be developed and understood.

In some instances, models and simulations did not demonstrate valid predictive capabilities, and there was an apparent lack of verification and validation of data and results, from a model or experiment or both, to connect the approach and underlying assumptions to real-world applications. In cases where data have not been validated, explicit plans to do so were not always explained or did not seem appropriate, clear, or adequate. In some cases, metrics and technical features of models or simulations were not explained in sufficient detail to permit their detailed assessment. At CISD, there is still not enough effort being made to ensure that mobile network models, especially when run in a multiscale, multilevel, end-to-end mode, are in fact reliable predictors of reality. In new areas of research at CISD, such as aerosol dispersion or ultrasonics in more complex environments (such as urban settings, with turbulence), researchers appeared to have some difficulty articulating what it takes to validate a new model. At CISD, particularly in projects involving complex computations, there remains a tendency to develop stand-alone codes, without any clear approach articulated for ensuring that both the algorithm modeling the physics and the implementation of that algorithm are correct.

WMRD is conducting work that applies modeling at different length scales (quantum through continuum) to describe the fracture behavior of AlON, and work that uses the optical response to ballistic impact in AlON and other transparent materials to understand stress, strain, and defects ahead of the actual fracture front, particularly the phenomenon described as “effective plasticity.” With respect to descriptions of these projects, numerous references were made by the panel to the lack of crisp success criteria, which makes it hard to know what properties or structures should be optimized. For example, what are the desired fragmentation size distributions for ceramic armor? Also, what is the desired mixture of static and dynamic failure prevention in ceramic armor? Without crisp success criteria, it remains difficult to understand the real goals of the substantial modeling and experimental efforts that are underway, or how they will be leveraged by the more applied engineering groups. ARL’s new MEDE Program is a promising approach to clarifying the goals and contributions of modeling and experimental efforts toward the achievement of application goals.

## Robotics and Autonomous Systems

The invention and use of robots on the battlefield will bring about the most profound change in warfare since the development of gunpowder. News stories now recount daily the results of drones piloted from Arizona and hitting targets of opportunity in the Afghanistan theater. As amazing as that may seem, we stand only at the threshold of change with respect to the impact that robots will have in future wars. Consistent with the importance of robots, the Army Research Laboratory has a large body of ongoing robotic research. During the past 2 years, the Board, through its various panels, has reviewed some of this research. While much interesting work is underway, several structural challenges should be addressed if these research programs are to achieve their potential.

A central concern is the limited contact of ARL researchers with the broader robotics community: ARL research projects generally seem to involve too little contact and collaboration with existing robot manufacturers, academics conducting robotic research, and other Army users of robots. This leads to the possibility of work that is duplicative or behind the state of the art. It is important that ARL researchers attend meetings at which they are exposed to the best of current external work in areas of interest and that they strive to publish their open research in the top-tier peer-reviewed journals in the field.

ARL should lead an effort with robot manufacturers, academia, and Army users to define the robotic capabilities that might be desired in a 2020 time frame. After 2020 capabilities are defined, ARL then needs to review its portfolio of research to ensure that its efforts are directed to areas in which it can make unique and important contributions. A benefit of such a review would be to foster cross-directorate interactions in the robotics area. Although it may be an artifact of the manner in which the panels are briefed, robotics work in one directorate often does not appear to make contact with relevant work elsewhere in ARL.

As ARL seeks to define areas in which it can have the most impact, two crosscutting areas seem promising: human-robotic interaction and robotic propulsion power density. Human-robotic interaction deals with how the robots will be deployed and controlled and how they will react to different battlefield challenges. At one end of the human-robotic interaction spectrum would be a single human in complete control of the robot; at the other end of the spectrum would be a completely autonomous robot. ARL has access to unique resources and data in this area and can contribute insights that would not be available from studies of interactions with robots that are cleaning house or building automobiles.

Robotic propulsion power determines the range, the time on station, and the payload of a robot. In particular, the combustion of Jet Propellant 8 fuel (JP-8) produces approximately two orders-of-magnitude-higher energy density than that of battery electric-type propulsion; therefore, ARL should concentrate on the combustion of JP-8 in very small, high-pressure-ratio systems.

## Computation and Modeling

Computational science involves the construction of mathematical models and quantitative analysis techniques of, generally, physical phenomena, followed by the use of computers to apply these models to explore a design space—often one that cannot be easily duplicated in reality. Challenges in computational science often occur in terms of scale: how the model or its implementation as a computer program changes as the problem changes. This scale can change in two ways. First, in a physics sense, multiscale models reflecting the conjoining of different models represent different levels of, usually, the physical world, such as a low-level atomic model for situations in which there are few atoms and/or in which small changes need to be tracked, whereas more bulk models are characterized by less accuracy but lower computational complexity. The second type of scale change reflects the relationship between problem size and the amount of computational resources used to solve it: in strong scaling, one keeps the problem size constant and increases the amount of computational resources in hopes of shortening the total solution time; in weak scaling, one wishes to increase the problem size as the computational resources increase, so that execution time remains constant. In terms of challenges to ARL, it is increasingly important that new models be designed from the start to be composable to multiscale, and that the right level of programming expertise in high-performance computing (HPC) be used to ensure that the resulting codes can scale either strongly or weakly as the application requires. ARL is addressing this challenge through two newly initiated programs in the evolving area of multiscale modeling and associated experimentation: the MEDE Program and the Multiscale Multidisciplinary Modeling of Electronic Materials Program. Each of these programs will involve cooperative research alliances that foster collaborative efforts among external institutions and with ARL researchers.

## Network Science

"Network science" is a term that covers a great deal of territory, and that territory has been growing. The networking efforts in ARL encompass two different concepts of a network. The first is the traditional view of a network as a collection of interconnected computing devices, and the questions asked are about the speeds or latency of transmission, perhaps versus the power expended to do the transmission. The second concept of networking involves a human (social) network, and it is the linkages between individuals revealing information about their intents that are important. Described in this way, these would seem to be two quite different domains making use of the same label. However, there is also a substantial area of overlap in which networks of humans are interacting through networks of devices. For an example of a topic that covers both domains, consider decision making by a distributed group, communicating over a network that introduces perceptible delays in the transmission of information. The behavior of the system is an interaction of the two types of networks.

ARL needs to provide strong scientific leadership in order to manage these different types of network science. ARL must decide where it can make an impact in the network sciences. Some topics will fall clearly within either CISD or HRED (see the individual directorate chapters for a discussion of those topics). Other topics bridge the directorates, and it will be important to coordinate the efforts across organizational boundaries. The Network Sciences Division of CISD, and its CTA, International Technology Alliance, and Mobile Network Modeling Institute were all formed with a primary focus on networks of computing devices. They appear to be moving to include issues involving networks of humans. Careful coordination between HRED, CISD, and other interested groups will be needed in order to provide appropriate financial and scientific resources for these different forms of network science.

## Energy Science

A great deal is being said in the greater power community about the future of smart grids and micropower. Stripped down to its fundamentals, micropower research is based on two related ideas:

1. *Power at the point of application is the real issue.* Power conversion, distribution, and consumption management are now included in every aspect of a system design, which can no longer be isolated in a single module interfaced at a power connector. For example, in modern microelectronics design, power and energy distribution and management primitives cut across every level of the design, from distribution networks in the physical design to energy and clock management in software. This multiscale design strategy for power and energy management is the future for almost all military systems.
2. *Power is an integral part of every aspect of a system design*. Such a system design is much more than a traditional load analysis. Designs for power conversion and distribution must include considerations of weight and thermal loading both locally and cumulatively. When considered in this way, priorities and practicalities are easier to identify, and solutions often become apparent.

With power and energy an integral part of an entire system design, successful systems will result from a collaborative effort that includes the designers of the power and energy systems and the designers of the systems that consume power and energy resources. Power management that is tightly integrated with information technologies has already been demonstrated to be a winning concept. This approach must be expanded to take in sensing, actuation, and communication systems as well as control systems, armor, and weapons systems. ARL must identify and support early and ongoing collaborations among individuals with power and energy expertise within SEDD and system designers in all of the other directorates. This will ensure that for future systems, power and energy issues are identified and solved early in the design process. One significant relevant approach underway at ARL is the Multiscale Multidisciplinary Modeling of Electronic Materials Program mentioned above.

## Materials by Design

In past eras, materials have been principally selected almost exclusively on the basis of hands-on experience with a material's characteristics—that is, the material was found or manufactured and then, based on its performance compared to that of other materials, was selected as the preferred material for a given application. This approach to materials selection applies to industrial practice in general and also to defense applications such as those in the Army. Engineering the response of metals and alloys to the desired end performance or application is an age-old trade, extending from the famous 5th-century steels of Damascus to the aluminum alloys that enabled the modern era of civilian aviation. This historical approach to materials and alloy development, sometimes crudely referred to as "cook and look," has been reflected in the mainstream Edisonian approach to developing new materials classes. Under this approach, a strong closed-loop linkage between processing and performance was established. The optimization of a material to meet the performance needs of a given application was most often, therefore, an iterative process of varying the processing, and accordingly the material's microstructure and its properties, to achieve the desired results in terms of performance.

Manufacturing recipes were typically developed through trial and error, but during the years leading up to World War II, scientists and engineers conducted the first systematic materials studies. As one example, significant research was focused on how the relationship between the applied stress, or force over area, and the resulting strain, or change in length, varied with temperature, strain rate, and stress state. Knowledge from that research was quickly applied to critical wartime needs: high-speed manufacturing of metal parts (including high-speed wire drawing and the cold rolling of metal parts) and advances in ballistics, avionics, and armor. Spin-offs from those early studies led to increasingly sophisticated materials of relevance to defense, transportation, and communications. Further, in this mode of materials development, the detailed quantification of the microstructure and properties of a material as a function of a diverse set of variables was developed as scientific understanding, and engineering predictive linkages were sought in order to accelerate materials development.

Over the past five decades, this initial coupling of processing know-how and experience with rules of thumb has given way, first, to an increasing level of scientific and engineering insight into the dominant mechanisms that control microstructure development linked to process modeling and, thereafter, to the predictive modeling of the correlations between microstructure, properties, and performance. This evolution in the process flow paradigm governing materials development to a rapidly accelerated level of using materials modeling to link processing to structure to properties to performance has seen great strides in recent years. Thus, researchers are now heralding a transition from the observation and validation of materials performance to the designing of materials to achieve tailored functionality through the utilization of multiscale materials modeling in order to predict accurately and to control performance.

In this evolving, new materials-design paradigm, the focus becomes geared to identifying new materials and microstructures that are theoretically predicted to meet a set of designer-specified performance criteria. This methodology encompasses two salient steps: (1) the identification of a set of microstructures that are theoretically predicted to meet or exceed a combination of the desired properties or performance goals, and (2) the identification of processing routes that are theoretically predicted to realize the desired optimized microstructures. This represents a decadal Grand Challenge to engineers and scientists: to develop tailored materials based on a body of knowledge founded on scientific mechanisms and the governing physics as opposed to empirical relationships fitted to experimental observations and testing. This turnaround in the design paradigm to the prediction and control of performance through the process-aware design of materials using predictive multiscale tools has been variously termed computational materials design, inverse materials design, materials by design, and integrated computational materials engineering.

In the new capability of predicting material behavior and designing and engineering custom materials with predetermined characteristics, materials are viewed as multiscale hierarchical systems. A critical aspect for achieving success in materials design is the availability of validated models that predict the processing-microstructure-property relationships in materials systems of interest. Given that the materials phenomena of relevance to research at ARL span a wide range of temporal and spatial scales, it is imperative that a linked multiscale modeling framework that passes information both to higher-length scales and to lower-length scales be developed. Meeting this need is particularly challenging in DoD, given the complexities in understanding and modeling processes such as armor penetration and munitions performance, which encompass complex physical and chemical processes. It is essential that the system of predictive models developed be tightly coupled throughout the design process to an efficient experimental system of model calibration, validation, and databases linking materials microstructures to properties and performance. Only through this linkage can the materials community, and the Army and its contractors in particular, hope to define accuracy through the quantification of model uncertainty and incorporate material statistics and heterogeneity. It is expected that the ARL Materials in Extreme

Dynamic Environments Program and Multiscale Multidisciplinary Modeling of Electronic Materials Program mentioned above will encourage intellectual and programmatic elements that will foster collaborative work for the integration of modeling, experimentation, and design in order to produce materials that address Army application needs.

## LINKAGE BETWEEN THE ARMY RESEARCH LABORATORY AND THE ARMY RESEARCH OFFICE

The Board is not charged to review the work funded by the Army Research Office (ARO), which is an organizational entity within ARL. ARO is a significant basic research asset with a significant fraction of the total ARL basic research (6.1) budget. Considering the important role that basic research has had in the development of Army-relevant technologies and the similar high-payoff role that it could have in the future, the Board requested an opportunity to learn how the work portfolio of ARO is integrated into the activities normally reviewed by the Board. In response, ARO presented to each panel summaries of those 6.1 programs that ARO sponsors which are relevant to the ARL work reviewed by the given panel and/or presented a summary of the organizational mechanisms by which ARO interacts with staff at the directorates. The level of ARO collaboration varies across the directorates. In general, ARO demonstrated increasing attention to such collaboration, and the Board looks forward to continuing improvements in ARO's cognizance and support of the missions of the directorates.

# Appendixes

# Appendix A

# Army Research Laboratory Organization Chart and Staffing Profile

This appendix presents an organization chart of the Army Research Laboratory (ARL) in Figure A.1 and data on ARL staffing in Table A.1. Table A.1 presents staffing profiles by directorate for the years 2004, 2006, 2008, and 2010.

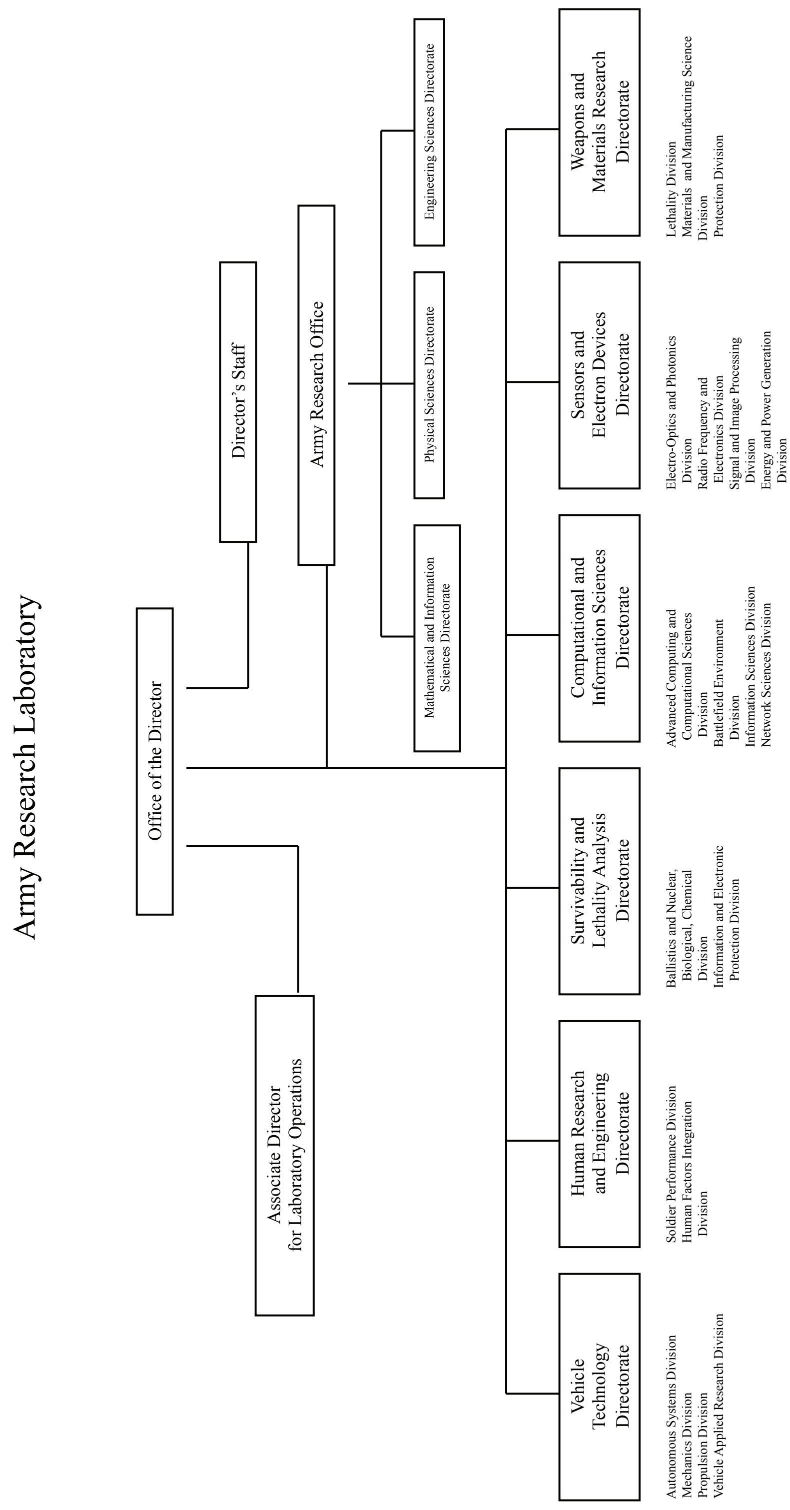


FIGURE A.1 Army Research Laboratory organization chart.

TABLE A.1 Army Research Laboratory Staffing Profiles, by Directorate, for the Years 2004, 2006, 2008, and 2010

| Staffing Information | | Number [%] | | | | | |
|---|---|---|---|---|---|---|---|
| | | CISD | HRED | SEDD | SLAD | VTD | WMRD |
| Total civilian staff | Dec-04 | 313 | 217 | 376 | 294 | 84 | 403 |
| | Jul-06 | 302 | 208 | 330 | 305 | 73 | 419 |
| | Jul-08 | 294 | 186 | 391 | 305 | 73 | 402 |
| | Jul-10 | 291 | 168 | 345 | 307 | 65 | 452 |
| Scientists and engineers | Dec-04 | 200 [64%] | 162 [75%] | 297 [79%] | 236 [80%] | 61 [73%] | 282 [70%] |
| | Jul-06 | 88 [62%] | 149 [72%] | 272 [82%] | 243 [80%] | 50 [68%] | 294 [70%] |
| | Jul-08 | 188 [64%] | 137 [74%] | 292 [75%] | 245 [80%] | 51 [70%] | 288 [72%] |
| | Jul-10 | 189 [65%] | 136 [81%] | 291 [84%] | 258 [84%] | 54 [83%] | 328 [73%] |
| Technicians | Dec-04 | 16 [5%] | 11 [5%] | 46 [12%] | 32 [11%] | 11 [13%] | 89 [22%] |
| | Jul-06 | 14 [5%] | 16 [8%] | 28 [9%] | 32 [10%] | 12 [17%] | 89 [21%] |
| | Jul-08 | 21 [7%] | 14 [8%] | 65 [17%] | 38 [12%] | 14 [19%] | 85 [21%] |
| | Jul-10 | 11 [4%] | 19 [11%] | 22 [6%] | 25 [8%] | 6 [9%] | 82 [19%] |
| Administrative personnel | Dec-04 | 97 [31%] | 44 [20%] | 33 [9%] | 26 [9%] | 12 [14%] | 32 [8%] |
| | Jul-06 | 100 [33%] | 43 [20%] | 30 [9%] | 30 [10%] | 11 [15%] | 36 [9%] |
| | Jul-08 | 85 [29%] | 35 [19%] | 34 [9%] | 22 [7%] | 8 [11%] | 29 [7%] |
| | Jul-10 | 91 [31%] | 13 [8%] | 30 [9%] | 24 [8%] | 5 [8%] | 30 [7%] |
| Military personnel | Dec-04 | 6 | 3 | 4 | 15 | 5 | 5 |
| | Jul-06 | 4 | 5 | 4 | 11 | 2 | 6 |
| | Jul-08 | 5 | 6 | 3 | 9 | 3 | 2 |
| | Jul-10 | 4 | 2 | 6 | 7 | 3 | 3 |
| Postdoctoral researchers | Dec-04 | 1 | 1 | 4 | 0 | 1 | 0 |
| | Jul-06 | 0 | 1 | 17 | 0 | 0 | 8 |
| | Jul-08 | 2 | 2 | 12 | 0 | 0 | 9 |
| | Jul-10 | 4 | 4 | 24 | 0 | 0 | 39 |
| Guest researchers | Dec-04 | 2 | 3 | 11 | 0 | 0 | 0 |
| | Jul-06 | 36 | 2 | 24 | 0 | 0 | 17 |
| | Jul-08 | 12 | 5 | 10 | 0 | 3 | 10 |
| | Jul-10 | 9 | 3 | 15 | 0 | 3 | 7 |
| On-site contractors | Dec-04 | 286 | 1 | 61 | 80 | 0 | 133 |
| | Jul-06 | 260 | 3 | 65 | 123 | 0 | 214 |
| | Jul-08 | 242 | 1 | 72 | 77 | 0 | 135 |
| | Jul-10 | 286 | 12 | 113 | 106 | 27 | 317 |

*Continued*

TABLE A.1 Continued

| Staffing Information | | Number [%] CISD | HRED | SEDD | SLAD | VTD | WMRD |
|---|---|---|---|---|---|---|---|
| B.S. or B.A. | Dec-04 | 80 [40%] | 64 [40%] | 85 [29%] | 136 [58%] | 23 [38%] | 101 [36%] |
| | Jul-06 | 58 [31%] | 35 [23%] | 52 [19%] | 121 [50%] | 9 [18%] | 87 [30%] |
| | Jul-08 | 65 [35%] | 40 [29%] | 87 [30%] | 134 [55%] | 23 [45%] | 89 [31%] |
| | Jul-10 | 51 [27%] | 27 [20%] | 57 [18%] | 128 [50%] | 12 [22%] | 75 [23%] |
| M.S. or M.A. | Dec-04 | 69 [35%] | 51 [31%] | 97 [32%] | 78 [33%] | 16 [26%] | 62 [22%] |
| | Jul-06 | 81 [43%] | 68 [46%] | 99 [37%] | 100 [41%] | 21 [42%] | 63 21%][a] |
| | Jul-08 | 69 [37%] | 41 [30%] | 90 [31%] | 85 [35%] | 11 [22%] | 66 [23%] |
| | Jul-10 | 84 [44%] | 57 [42%] | 98 [31%] | 112 [43%] | 18 [33%] | 95 [29%] |
| Ph.D. | Dec-04 | 51 [25%] | 47 [29%] | 115 [39%] | 22 [9%] | 22 [36%] | 119 [42%] |
| | Jul-06 | 49 [26%] | 46 [31%] | 120 [44%] | 22 [9%] | 20 [40%] | 144 [49%] |
| | Jul-08 | 49 [26%] | 50 [36%] | 111 [38%] | 18 [7%] | 16 [31%] | 123 [43%] |
| | Jul-10 | 54 [29%] | 50 [37%] | 149 [49%] | 18 [7%] | 24 [44%] | 158 [48%] |
| Under 25 years of age | Dec-04 | 11 [6%] | 14 [9%] | 8 [3%] | 19 [8%] | 0 [0%] | 8 [3%] |
| | Jul-06 | 5 [3%] | 7 [5%] | 9 [3%] | 12 [5%] | 0 [0%] | 7 [2%] |
| | Jul-08 | 6 [3%] | 1 [1%] | 9 [3%] | 11 [4%] | 0 [0%] | 0 [0%] |
| | Jul-10 | 4 [2%] | 5 [4%] | 3 [1%] | 4 [2%] | 1 [1%] | 4 [1%] |
| 25-35 years of age | Dec-04 | 19 [10%] | 25 [15%] | 33 [11%] | 18 [8%] | 7 [12%] | 48 [17%] |
| | Jul-06 | 24 [13%] | 25 [17%] | 34 [13%] | 39 [16%] | 6 [8%] | 39 [13%] |
| | Jul-08 | 27 [14%] | 24 [18%] | 48 [16%] | 48 [20%] | 5 [10%] | 52 [18%] |
| | Jul-10 | 27 [14%] | 26 [19%] | 55 [16%] | 64 [25%] | 11 [17%] | 94 [21%] |
| 35-45 years of age | Dec-04 | 63 [31%] | 36 [22%] | 112 [38%] | 82 [35%] | 28 [46%] | 97 [34%] |
| | Jul-06 | 48 [26%] | 35 [23%] | 87 [32%] | 72 [30%] | 22 [30%] | 98 [33%] |
| | Jul-08 | 35 [19%] | 30 [22%] | 60 [21%] | 49 [20%] | 11 [22%] | 75 [26%] |
| | Jul-10 | 37 [20%] | 25 [18%] | 60 [17%] | 39 [15%] | 11 [17%] | 105 [23%] |
| 45-55 years of age | Dec-04 | 65 [32%] | 53 [33%] | 81 [27%] | 65 [27%] | 14 [23%] | 74 [26%] |
| | Jul-06 | 65 [35%] | 46 [31%] | 86 [32%] | 76 [31%] | 31 [43%] | 78 [27%] |
| | Jul-08 | 73 [39%] | 42 [31%] | 113 [39%] | 100 [41%] | 23 [45%] | 94 [33%] |
| | Jul-10 | 81 [43%] | 39 [29%] | 140 [41%] | 101 [39%] | 31 [48%] | 161 [36%] |
| 55-65 years of age | Dec-04 | 36 [18%] | 28 [17%] | 52 [17%] | 42 [18%] | 10 [16%] | 50 [18%] |
| | Jul-06 | 39 [21%] | 30 [20%] | 44 [16%] | 36 [15%] | 13 [18%] | 66 [22%] |
| | Jul-08 | 37 [20%] | 31 [23%] | 48 [16%] | 31 [13%] | 11 [22%] | 55 [19%] |
| | Jul-10 | 30 [16%] | 35 [26%] | 66 [19%] | 43 [17%] | 7 [11%] | 71 [16%] |

TABLE A.1 Continued

| Staffing Information | | Number [%] CISD | HRED | SEDD | SLAD | VTD | WMRD |
|---|---|---|---|---|---|---|---|
| Over 65 years of age | Dec-04 | 6 [3%] | 6 [4%] | 11 [4%] | 10 [4%] | 2 [3%] | 5 [2%] |
| | Jul-06 | 7 [4%] | 6 [4%] | 12 [4%] | 8 [3%] | 1 [1%] | 6 [2%] |
| | Jul-08 | 10 [5%] | 8 [6%] | 14 [5%] | 6 [2%] | 1 [2%] | 12 [4%] |
| | Jul-10 | 10 [5%] | 6 [4%] | 24 [7%] | 7 [3%] | 4 [6%] | 17 [4%] |

NOTE: CISD, Computational and Information Sciences Directorate; HRED, Human Research and Engineering Directorate; SEDD, Sensors and Electron Devices Directorate; SLAD, Survivability and Lethality Analysis Directorate; VTD, Vehicle Technology Directorate; WMRD, Weapons and Materials Research Directorate.
SOURCE: Army Research Laboratory.

# Appendix B

# Membership of the Army Research Laboratory Technical Assessment Board and Its Panels

This appendix presents biographical sketches of the members of the Army Research Laboratory Technical Assessment Board, followed by listings of the members of the panels and their affiliations.

## BIOGRAPHICAL SKETCHES OF MEMBERS: ARMY RESEARCH LABORATORY TECHNICAL ASSESSMENT BOARD

LYLE H. SCHWARTZ, *Chair,* is a member of the National Academy of Engineering, retired director of the Air Force Office of Scientific Research (AFOSR), and currently a senior research scientist with the Department of Materials Science and Engineering at the University of Maryland. He was a professor of materials science and engineering at Northwestern University for 20 years and the director of Northwestern's Materials Research Center for 5 of those years. He then became the director of the Materials Science and Engineering Laboratory at the National Institute of Standards and Technology, where he served for more than 12 years. His responsibilities included management of the research and development (R&D) agenda in the context of a government laboratory. Dr. Schwartz subsequently assumed responsibility for basic research on structural materials of interest to the U.S. Air Force, in addition to the areas of propulsion, aeromechanics, and aerodynamics. He then completed his government service as director of the AFOSR with responsibility for the entire basic research program of the Air Force. His current interests include government policy for R&D, particularly for materials R&D; materials science education at K-12 levels; and enhanced public understanding of the roles and importance of technology in society. Dr. Schwartz received both his B.S. in engineering and Ph.D. in materials science from Northwestern University.

DONALD M. CHIARULLI is a professor of computer science and computer engineering at the University of Pittsburgh. His expertise includes experimental computer architecture, and optics and optoelectronics for dense interconnection networks. In the context of building experimental systems, his work also includes a significant effort in the development of new design tools for the modeling and simulation of these systems. Dr. Chiarulli holds patents in computer and related optical and optoelectronic hardware. His current research work is in the areas of chip-level optoelectronic interconnections, optical-electronic-mechanical multidomain computer-aided design, optical memory systems, robotics, and voice input/speech output interfaces for embedded system applications. He received his Ph.D. in computer science from Louisiana State University.

DAVID E. CROW, a member of the National Academy of Engineering, is retired senior vice president of engineering at Pratt and Whitney Aircraft Engine Company. He is also currently a professor of mechanical engineering at the University of Connecticut. At Pratt and Whitney he was influential in design, development, testing, and manufacturing in support of a full line of engines for aerospace and industrial applications. Dr. Crow was involved with products that include high-thrust turbofans for large commercial and military aircraft, turboprops and small turbofans for regional and corporate aircraft and helicopters, booster engines and upper-stage propulsion systems for advanced launch vehicles, turbopumps for the space shuttle, and industrial engines for land-based power generation. His involvement included sophisticated computer modeling and standards work to bring constant improvements in the performance and reliability of the company's products while at the same time reducing noise and emissions.

MARJORIE ERICKSON is an expert both in the development of physics-based models of material behavior in the prediction of material failure and in the performing of risk assessments. Dr. Erickson is the president of Phoenix Engineering Associates, Inc., and an adjunct professor of mechanical engineering at the University of Maryland. She conducts research and consults with industry regarding fracture safety assessment methodology for steel and other alloy components. She provides these services in the areas of assessing the integrity and durability of civil, mechanical, and marine structures fabricated from metallic materials. Specific work that Dr. Erickson has performed includes developing and using integrated, predictive models of material behavior to assess the current status and predict the remaining safe life, under known or expected operating and accident-event conditions, for nuclear pressure vessels and other alloy applications, including fracture safety assessment and life extension of aging aircraft and pipelines. Dr. Erickson received her Ph.D. in materials science from the University of Virginia.

GEORGE T. GRAY III is a Laboratory Fellow and staff member in the dynamic properties and constitutive modeling team in the Materials Science Division of the Los Alamos National Laboratory (LANL). He came to LANL after holding a 3-year visiting scholar position at the Technical University of Hamburg-Harburg in Hamburg, Germany, having received his Ph.D. in materials science in 1981 from Carnegie Mellon University. As a staff member (1985-1987) and later team leader (1987-2003) in the Dynamic Materials Properties and Constitutive Modeling Section in the Structure/Property Relations Group (MST-8) at LANL, Dr. Gray has directed a research team working on investigations of the dynamic response of materials. He conducts fundamental, applied, and focused programmatic research on materials and structures, in particular in response to high-strain-rate and shock deformation. His research is focused on experimental and modeling studies of substructure evolution and mechanical response of materials. These constitutive and damage models are used in engineering computer codes to support large-scale finite element modeling simulations of structures including those involved in national defense (Department of Energy, Department of Defense, Defense Advanced Research Projects Agency); industry (GM, Ford, Chrysler, and Bettis); foreign object damage; and manufacturing. Dr.

Gray is a life member of Clare Hall, Cambridge University, where he was on sabbatical in the summer of 1998. He co-chaired the Physical Metallurgy Gordon Conference in 2000 and currently serves on the board of directors of the Minerals, Metals, and Materials Society (TMS) as the chair of Publications. He is a fellow of the American Physical Society (APS); a fellow of ASM International; and a member of APS, ASM International, and TMS; he also serves on the International Scientific Advisory Board of the European DYMAT Association. He serves on the *Acta Materialia* Board of Governors. He is currently the president of TMS. He has authored or co-authored more than 330 technical publications.

PETER M. KOGGE is the associate dean of engineering for research and holds the McCourtney Chair in Computer Science and Engineering (CSE) at the University of Notre Dame. Before joining Notre Dame in 1994, he was with the IBM Federal Systems Division, and he was appointed an Institute of Electrical and Electronics Engineers fellow in 1990 and an IBM fellow in 1993. In 1977, Dr. Kogge was a visiting professor in the Electrical and Computer Engineering Department at the University of Massachusetts, Amherst. From 1977 through 1994, he was an adjunct professor in the Computer Science Department of the State University of New York at Binghamton. Since the summer of 1997, he has been a distinguished visiting scientist at the Center for Integrated Space Microsystems at the Jet Propulsion Laboratory. He is also the Research Thrust Leader for Architecture in Notre Dame's Center for Nano Science and Technology. For the 2000-2001 academic year, Dr. Kogge was the interim Schubmehl-Prein Chairman of the CSE Department at Notre Dame. Since the fall of 2003, he has also been a concurrent professor of electrical engineering. His research interests are in advanced computer architectures using unconventional technologies, such as processing-in-memory, and nanotechnologies, such as quantum-dot cellular automata.

JEREMY M. WOLFE is a professor of ophthalmology and radiology at Harvard Medical School and director of the Visual Attention Lab and of the Radiology Department's Center for Advanced Medical Imaging at Brigham and Women's Hospital. In addition, he is a visiting faculty member in the Department of Brain and Cognitive Sciences at the Massachusetts Institute of Technology (MIT) and an adjunct associate professor in cognitive and neural systems at Boston University. He has extensive expertise in vision, binocular perception, visual attention, and cognitive science. Dr. Wolfe has received numerous honors and awards throughout his career and holds memberships in a number of prominent professional societies and organizations. He has authored 112 published papers, 1 textbook, and 26 book chapters. He received his Ph.D. in psychology from MIT.

## Staff

JAMES P. McGEE is the director of the Laboratory Assessments Board, the Army Research Laboratory Technical Assessment Board (ARLTAB), and the Committee on National Institute of Standards and Technology Technical Programs, in the Division on Engineering and Physical Sciences at the National Research Council (NRC). Since 1994, he has been a senior staff officer at the NRC, directing projects in the areas of systems engineering and applied psychology, including activities of ARLTAB and projects of the Committee on National Statistics' (CNS's) Panel on Operational Testing and Evaluation of the Stryker Vehicle and CNS's Committee on Assessing the National Science Foundation's Scientists and Engineers Statistical Data System, the Committee on the Health and Safety Needs of Older Workers, and the Steering Committee on Differential Susceptibility of Older Persons to Environmental Hazards. He has also served as staff officer for NRC projects on Air Traffic Control Automation, Musculoskeletal Disorders and the Workplace, and the Changing Nature of Work. Prior to joining the NRC, Dr.

McGee held technical and management positions in systems engineering and applied psychology at IBM, General Electric, RCA, General Dynamics, and United Technologies corporations. He received his B.A. from Princeton University and his Ph.D. from Fordham University, both in psychology, and for several years instructed postsecondary courses in applied psychology and in organizational management.

ARUL MOZHI is a senior program officer at the Laboratory Assessments Board in the Division on Engineering and Physical Sciences at the National Research Council (NRC). Since 1999, he has been a senior program officer at the NRC, directing projects in the areas of defense science and technology, including those carried out by numerous study committees of the Laboratory Assessments Board, the Army Research Laboratory Technical Assessment Board, the Naval Studies Board, the National Materials Advisory Board, and the Board on Manufacturing and Engineering Design. Prior to joining the NRC, Dr. Mozhi held technical and management positions in systems engineering and applied materials research and development at UTRON, Inc.; Roy F. Weston, Inc.; and Marko Materials, Inc. He received his M.S. and Ph.D. degrees (the latter in 1986) in materials engineering from the Ohio State University and then served as a postdoctoral research associate there. He received his B.S. in metallurgical engineering from the Indian Institute of Technology in 1982.

LIZA HAMILTON is the administrative coordinator for the Laboratory Assessments Board in the Division on Engineering and Physical Sciences at the National Research Council (NRC). Since 2002, she has been responsible for managing the administrative aspects of panel formation, panel meetings, report publication and dissemination, and program development. In addition, she has designed newsletters, brochures, cover designs, and figures for numerous reports prepared by the NRC's Division on Life Sciences and Division on Engineering and Physical Sciences. Ms. Hamilton earned a 4- year certification in musical theater performance from Pinellas County Center for the Arts in St. Petersburg, Florida; a B.F.A. in film studies from the University of Utah; a design certification from Maryland Institute College of Art; and a Master's of Liberal Arts from the Johns Hopkins University.

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## PANEL ROSTERS

### Panel on Air and Ground Vehicle Technology

David Crow, Pratt & Whitney Aircraft Engine Company (retired), *Chair*
Ralph Aldredge, University of California, Davis
James Bettner, Propulsion Consultant, Pittsboro, Indiana
Paul Bevilaqua, Lockheed Martin Aeronautics Company
Earl Dowell, Duke University
Ephrahim Garcia, Cornell University
Prabhat Hajela, Rensselaer Polytechnic Institute
James Hamilton, Target Chip Ganassi Racing
S. Michael Hudson, Rolls-Royce North American Technologies, Inc. (retired)
William McCroskey, NASA Ames Research Center
Robin R. Murphy, Texas A&M University
Lynne Parker, University of Tennessee
Neil Paton, Liquidmetal Technologies
Martin Peryea, Bell Helicopter Textron, Inc.
Kenneth Reifsnider, University of South Carolina
William Sirignano, University of California, Irvine
Christine Sloane, General Motors Corporation
Michael Torok, Sikorsky Aircraft Corporation
Ronald York, Rolls-Royce North American Technologies, Inc.

### Panel on Armor and Armaments

George (Rusty) Gray III, Los Alamos National Laboratory, *Chair*
Thomas Eagar, Massachusetts Institute of Technology
Mark Eberhart, Colorado School of Mines
Katharine Frase, IBM Corporation
Rigoberto Hernandez, Georgia Institute of Technology
John W. Hutchinson, Harvard University
Clarence W. "Wes" Kitchens, Jr., Wes Kitchens and Associates, LLC
Stelios Kyriakides, University of Texas at Austin
Paul A. Lagace, Massachusetts Institute of Technology
R. Bowen Loftin, Texas A&M University
Gregory Miller, University of California, Davis
Jimmie C. Oxley, University of Rhode Island
George C. Schatz, Northwestern University
Eugene Sevin, Lyndhurst, Ohio
Steven F. Son, Purdue University
Leonard Uitenham, North Carolina Agricultural and Technical State University

### Panel on Digitization and Communications Science

Peter Kogge, University of Notre Dame, *Chair*
Steven Bellovin, Columbia University

Keren Bergman, Columbia University
Willard Bolton, Sandia National Laboratories
David Borth, Motorola, Inc.
L. Reginald Brothers, Jr., BAE Systems
Gary Brown, Virginia Polytechnic Institute and State University
Lori Freitag Diachin, Lawrence Livermore National Laboratory
William Gropp, University of Illinois at Urbana-Champagne
Mary Jane Irwin, Pennsylvania State University
Christina B. Katsaros, Northwest Research Associates, Inc.
Thomas L. Koch, Lehigh University
Juan C. Meza, Lawrence Berkeley National Laboratory
Debasis Mitra, Bell Labs, Alcatel-Lucent
Robert Lucas, University of Southern California
Tamar Peli, Charles Stark Draper Laboratory, Inc.
Mikel Petty, University of Alabama, Huntsville
Padma Raghavan, Pennsylvania State University
John Snow, University of Oklahoma
Michael Walfish, University of Texas at Austin

## Panel on Sensors and Electron Devices

Donald Chiarulli, University of Pittsburgh, *Chair*
Eli Brookner, Raytheon Company
J. Patrick Fitch, National Biodefense Analysis and Countermeasures Center
Thomas Fuller, Georgia Institute of Technology
George I. Haddad, University of Michigan
Herbert Hess, University of Idaho
Paul Hoff, Independent Consultant, Bedford, New Hampshire
Evelyn L. Hu, Harvard University
Douglas Mook, The Aptec Group
Michael G. Spencer, Cornell University
Levi Thompson, University of Michigan
Anil V. Virkar, University of Utah

## Panel on Survivability and Lethality Analysis

Marjorie Erickson, Phoenix Engineering Associates, Inc., *Chair*
David Aucsmith, Microsoft Corporation
David Barton, Independent Consultant, Hanover, New Hampshire
Gerald G. Brown, U.S. Naval Postgraduate School
Thomas Burris, Lockheed Martin Aeronautics Company
Alan Jones, The Boeing Company
Ronald R. Luman, Johns Hopkins University
Guruswami Ravichandran, California Institute of Technology
Stephen M. Robinson, University of Wisconsin-Madison
Marlin U. Thomas, Air Force Institute of Technology

## Soldier Systems Panel

Jeremy Wolfe, Harvard Medical School, *Chair*
Julie Adams, Vanderbilt University
Theodore Berger, University of Southern California
Tora Bikson, The RAND Corporation
Linda Ng Boyle, University of Washington
Michael Byrne, Rice University
Terry Connolly, University of Arizona
Paul W. Glimcher, New York University
Steven Hyman, Harvard University
Daniel Ilgen, Michigan State University
Gerald Krueger, Krueger Ergonomics Consultants, Vienna, Virginia
William S. Marras, The Ohio State University
Emilie Roth, Roth Cognitive Engineering
Gavriel Salvendy, Purdue University
Thomas Sanquist, Pacific Northwest National Laboratory
Richard Thompson, University of Southern California
Charles S. Watson, Indiana University
Arthur Wingfield, Brandeis University

# Appendix C

# Assessment Criteria

The Army Research Laboratory Technical Assessment Board's assessment considered the following general questions posed by the ARL Director:

1. Is the scientific quality of the research of comparable technical quality to that executed in leading federal, university, and/or industrial laboratories both nationally and internationally?
2. Does the research program reflect a broad understanding of the underlying science and research conducted elsewhere?
3. Does the research employ the appropriate laboratory equipment and/or numerical models?
4. Are the qualifications of the research team compatible with the research challenge?
5. Are the facilities and laboratory equipment state of the art?
6. Does the research reflect an understanding of the Army's requirement for the research or the analysis?
7. Are programs crafted to employ the appropriate mix of theory, computation, and experimentation?
8. Is the work sufficiently unique and appropriate to the ARL niche?
9. Are there especially promising projects that, with application of adequate resources, could produce outstanding results that could be transitioned ultimately to the field?

The Board applied the following metrics or criteria to the assessment of the scientific and technical work reviewed at the Army Research Laboratory (ARL):

1. Effectiveness of Interaction with the Scientific and Technical Community
   a. Papers in quality refereed journals and conference proceedings (and their citation index)
   b. Presentations and colloquia
   c. Participation in professional activities (society officers, conference committees, journal editors)

   d. Educational outreach (serving on graduate committees, teaching or lecturing, invited talks, mentoring students)
   e. Fellowships and awards (external and internal)
   f. Review panel participation (Army Research Office, National Science Foundation, Multidisciplinary University Research Initiative)
   g. Recruiting new talent into the ARL
   h. Patents and intellectual property (IP) (and examples of how the patent or IP is used)
   i. Involvement in building an ARL-wide cross-directorate community
   j. Public recognition (e.g., in the press and elsewhere) for ARL research

2. Impact on Customers
   a. Documented transfer or transition of technology, concepts, or program assistance from ARL to Research, Development, and Engineering Centers (RDECs) or RDEC contractors for both the long term and short term
   b. Direct funding from customers to support ARL activities
   c. Documented demand for ARL support or services (is there competition for ARL's support?)
   d. Customer involvement in directorate planning
   e. Participation in multidisciplinary, cross-directorate projects
   f. Surveys of customer base (direct information from customers on value of ARL research)

3. Formulation of Projects' Goals and Plans
   a. Is there a clear tie to ARL Strategic Focus Areas, Strategic Plan, or other ARL need?
   b. Are tasks well defined to achieve objectives?
   c. Does the project plan clearly identify dependencies (i.e., successes depend on success of other activities within the project or outside developments)?
   d. If the project is part of a wider activity, is role of the investigators clear, and are the project tasks and objectives clearly linked to those of other related projects?
   e. Are milestones identified if they are appropriate? Do they appear feasible?
   f. Are obstacles and challenges defined (technical, resources)?
   g. Does the project represent an area where application of ARL strengths is appropriate?

4. Research and Development Methodology
   a. Are the hypotheses appropriately framed within the literature and theoretical context?
   b. Is there a clearly identified and appropriate process for performing required analyses, prototypes, models, simulations, tests, etc.?
   c. Are the methods (e.g., laboratory experiment, modeling or simulation, field test, analysis) appropriate to the problems? Do these methods integrate?
   d. Is the choice of equipment or apparatus appropriate?
   e. Is the data collection and analysis methodology appropriate?
   f. Are conclusions supported by the results?
   g. Are proposed ideas for further study reasonable?
   h. Do the trade-offs between risk and potential gain appear reasonable?
   i. If the project demands technological or technical innovation, is that occurring?
   j. What stopping rules, if any, are being or should be applied?

5. Capabilities and Resources
   a. Are the qualifications and number of the staff (scientific, technical, administrative) appropriate to achieve success of the project?
   b. Is funding adequate to achieve success of the project?
   c. Is the state of the equipment and facilities adequate?
   d. If staff, funding, or equipment is not adequate, how might the project be triaged (what thrust should be emphasized, what sacrificed?) to best move toward its stated objectives?
   e. Does the laboratory sustain the technical capability to respond quickly to critical issues as they arise?

6. Responsiveness to the Board's Recommendations
   a. Have the issues and recommendations presented in the previous report been addressed?

# Appendix D

# Acronyms

| | |
|---|---|
| A2SF | Advanced All-Source Fusion |
| AC&CSD | Advanced Computing and Computational Sciences Division |
| AC2T | Academic Class Composite Tool |
| ACM | Association for Computing Machinery |
| AEC | Army Evaluation Center |
| AFOSR | Air Force Office of Scientific Research |
| AFRL | Air Force Research Laboratory |
| AHAAH | Auditory Hazard Assessment Algorithm for Humans |
| AMRDEC | Aviation and Missile Research, Development and Engineering Center |
| APS | active protection system |
| ARL | Army Research Laboratory |
| ARLTAB | Army Research Laboratory Technical Assessment Board |
| ARO | Army Research Office |
| ATO | Army Technology Objective |
| BED | Battlefield Environment Division |
| BND | Ballistics and Nuclear, Biological, and Chemical Division |
| BRAC | base realignment and closure |
| BRL-CAD | Ballistic Research Laboratory–Computer-Aided Design |
| CAD | computer-aided design |
| CASEL | Cognitive Assessment, Simulation, and Engineering Laboratory |
| CC | capability concept |
| CERDEC | Communications-Electronics Research, Development, and Engineering Center |

| | |
|---|---|
| CFD | computational fluid dynamics |
| CIO/G-6 | Office of the Chief Information Officer |
| CISD | Computational and Information Sciences Directorate |
| COTS | commercial-off-the-shelf |
| CTA | Collaborative Technology Alliance |
| DARPA | Defense Advanced Research Projects Agency |
| DE | directed energy |
| DFT | density functional theory |
| DoD | Department of Defense |
| DOE | Department of Energy |
| DSI | Director's Strategic Initiative |
| DU | depleted uranium |
| EAR | Environment for Auditory Research |
| ECAE | equal channel angle extrusion |
| EEG | electroencephalogram |
| EFP | explosively formed penetrator |
| EM | electromagnetic |
| EMVAF | Electro Magnetic Vulnerability Assessment Facility |
| EOCM | electro-optic countermeasures |
| FAST | Field Assistance in Science and Technology |
| FCS | Future Combat Systems |
| FEA | finite element analysis |
| FEM | finite element model |
| fMRI | functional magnetic resonance imaging |
| FPGA | field-programmable gate array |
| FY | fiscal year |
| GCV | Ground Combat Vehicle |
| GLEEM | Gun Liner Emplacement by Elastomeric Materials |
| GPS | Global Positioning System |
| HPC | high-performance computing |
| HRED | Human Research and Engineering Directorate |
| HRI | Human Robot Interaction |
| HSI | Human System Integration |
| ICA | independent component analysis |
| IED | improvised explosive device |
| IEEE | Institute of Electrical and Electronics Engineers |
| IEPD | Information and Electronic Protection Division |
| IM | insensitive munitions |
| IMPRINT | Improved Performance Research Integration Tool (software) |
| IMU | inertial measurement unit |

| | |
|---|---|
| INSCOM | Intelligence Security Command |
| IO | information operations |
| IR | infrared |
| IRCM | infrared countermeasures |
| ISD | Information Sciences Division |
| ISR | intelligence, surveillance, and reconnaissance |
| ITA | International Technology Alliance |
| | |
| JP-8 | Jet Propellant 8 fuel |
| | |
| LED | light-emitting diode |
| LIFE | Laser IRCM Flyout Experiment |
| LWIR | long-wavelength infrared |
| | |
| MANPRINT | Manpower and Personnel Integration |
| MASINT | Measurement and Signature Intelligence |
| MAST | Micro-Autonomous Systems and Technology |
| MBT&E | Mission-Based Test and Evaluation |
| MEDE | Materials in Extreme Dynamic Environments |
| MEMS | microelectromechanical systems |
| MMF | Mission and Means Framework (software) |
| MRAP | mine-resistant ambush-protected |
| MT | machine translation |
| MURI | Multidisciplinary University Research Initiative |
| MUVES | Modular UNIX-based Vulnerability Estimation Suite (software) |
| | |
| NASA | National Aeronautics and Space Administration |
| NDE | nondestructive evaluation |
| NRC | National Research Council |
| NSD | Network Sciences Division |
| | |
| OCR | optical character recognition |
| ODE | ordinary differential equation |
| ODT | omnidirectional treadmill |
| ONR | Office of Naval Research |
| OSD | Office of the Secretary of Defense |
| | |
| PASS | Personal Academic Strategies for Success |
| PTSD | post-traumatic stress disorder |
| | |
| QAM | quadrature amplitude modulation |
| | |
| R&D | research and development |
| RDEC | Research, Development, and Engineering Center |
| RDECOM | Research, Development, and Engineering Command |
| RF | radio frequency |

| | |
|---|---|
| S&T | science and technology |
| S4 | System of Systems Survivability Simulation (software) |
| SAFTE | Sleep, Activity, Fatigue and Task Effectiveness |
| SBAM | Scalable Binary Annular Munition |
| SBIR | Small Business Innovation Research |
| SEDD | Sensors and Electron Devices Directorate |
| SIRE | Synchronous Impulse Reconstruction |
| SLAD | Survivability and Lethality Analysis Directorate |
| SLV | survivability, lethality, and vulnerability |
| SLVA | survivability, lethality, and vulnerability assessment |
| SNA | social network analysis |
| SoS | system of systems |
| SoSA | system-of-systems analysis |
| SPEAR | Soldier Performance and Equipment Advanced Research |
| | |
| TARDEC | Tank Automotive Research, Development, and Engineering Center |
| TBI | traumatic brain injury |
| T&E | testing and evaluation |
| THINK | Tactical Human Integration of Networked Knowledge |
| TILV | Target Interaction Lethality/Vulnerability |
| TNT | 2,4,6-trinitrotoluene |
| TRADOC | Training and Doctrine Command |
| TTPs | tactics, techniques, and procedures |
| TWV | tactical wheeled vehicle |
| | |
| UAS | unmanned autonomous system |
| UAV | unmanned aerial vehicle |
| UGV | unmanned ground vehicle |
| UV | ultraviolet |
| | |
| V&V | validation and verification |
| VAATE | Versatile Affordable Advanced Turbine Engines Program |
| VAPP | Very Affordable Precision Projectile |
| VARD | Vehicle Applied Research Division |
| VSL | Virtual Shot Line |
| VTD | Vehicle Technology Directorate |
| VTOL | vertical take off and landing |
| | |
| WFO | warfighter outcome |
| WMRD | Weapons and Materials Research Directorate |