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Suggestions for Evaluating the Quality of the Army's Science and Technology Program: The Portfolio and Its Execution

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CONTENTS

I. INTRODUCTION

The U.S. Department of Defense (DOD) Deputy Assistant Secretary of the Army for Research and Technology requested that the Center for Technology and National Security Policy (CTNSP) suggest approaches to evaluating the quality of the current U.S. Army Science and Technology (S&T) portfolio and the quality of its execution. This paper contains the results of both studies.

There are two aspects of the U.S. Army S&T program that are evaluated in this paper: the portfolio and the quality of its execution. This paper poses the questions that should be asked. Emphasis for the analysis of the portfolio is on program content, the distribution of resources over the component parts of the portfolio, and the priorities among the parts. Normally in an assessment of this type it is necessary to identify the principal stakeholders and customers for the research and development program. In the case of Army S&T, the stakeholders are the senior leaders of the Army, DOD, Congress, and, ultimately, the American taxpayer. The customers are the U.S. Army warfighters. The study begins by outlining a clear statement of the vision and mission of the parent organization—the U.S. Army. We continue by describing in detail the needs and requirements of the U.S. Army by the Training and Doctrine Command (TRADOC), the Army senior leadership, and from various intermediary customers such as the U.S. Army Research, Development and Engineering Command and its components, and the Program Executive Offices and the Program Managers of the acquisition community. The discussion then turns to the mechanisms by which the portfolio is assembled and approved, as well as the limitations posed by the realities of the budget details of resource allocation.

To be in tune with the Army's needs now and into the future means that the portfolio should have a balance of programs between long-term basic research**,** medium-term applied research, and short-term work that can be transitioned into advanced development and beyond. The amount of work in each category will vary according to the nature of the individual laboratory's assignment. Also there is a balance between the work done in-house and that done extramurally on contracts and grants to the private sector or by other government laboratories.

To assess the quality of the execution of the program requires evaluating the strength of the Army laboratory system in terms of its managers, its technical staff, and available facilities and equipment. This evaluation can best be done by some form of peer review by subject matter experts. Additional evaluations should be made by the Army S&T Office, bringing in long-range technology forecasting to assure that the laboratory system will be prepared for future demands. Some form of benchmarking is needed to assess where the best work can be done. Collaborations can then be established, typically by contracts and grants to outside laboratories.

The objective is to have the strongest possible technology program appropriately aligned to the needs of its customers and the expectations of its stakeholders. In this paper we present methodology that should accomplish this goal. In chapter II, we first present the essential elements of the Army S&T portfolio. The chapters that follow describe the Army S&T portfolio and the evaluation of it, the evaluation of the quality of the program of execution, and a summary of the report.

II. THE CURRENT ARMY S&T PORTFOLIO

Analysis of the portfolio should begin with a study of how the current portfolio came into being. It is based on a long series of budget decisions made by the Army and Congress. These decisions were based on the threats facing the Army at the time and with forecasts of likely threats in the future. When we are at war, the laboratories are necessarily more focused on the short term. In the 2000s the intense focus on the wars in Afghanistan and Iraq and development of the Future Combat System shortened the time frame of the S&T program. Recent studies have expressed concern that the current time frame is too short.[1] The Army is now undergoing a period of force rebalancing and downsizing. The mission is shifting away from counterinsurgency in Afghanistan and Iraq to the Asia-Pacific region.

With the end of the Cold War, the Army underwent a dramatic downsizing. The S&T program was markedly reduced, sometimes by as much as one-half in budgetary terms. The reduction in the laboratory budgets removed many programs of lower priority; overhead costs were reduced to a minimum. This belt tightening left the most important research programs intact. The past decade of counterinsurgency led to some of the budget reductions being restored to mount programs directed at the wars in the Middle East.

Also during the 1990s and beyond, the Army S&T management turned outward in the sense that it established some very large extramural collaborations. Centers of excellence included the Institute for Soldier Nanotechnology, the Institute for Creative Technologies, and the Institute for Collaborative Biotechnologies. The Army also has funded the Institute for Applied Technology at the University of Texas for studies of electric guns. The focus of this work has recently been transferred to the United States navy. These institutes are university-based, involve several different disciplines, and consist of formal or informal consortia from industry and academe. A similar approach was used in the creation of several extramural consortia comprising academic and industrial members at the Army Research Laboratory (ARL). These consortia were tied closely to in-house ARL programs in that normal grants and contracts are operated at arm's length from the in-house staff, that is, once the contract or grant is awarded, interaction with Army personnel is not required until renewal discussions are held. These ARL collaborative centers of excellence—Collaborative Technology Alliances and Collaborative Research Alliances—differ from ordinary external centers of excellence in that they are designed to operate parallel with in-house research conducted by Army laboratory staff with the very best people in the private sector. This type of management involves rotation of staff into and out of the Army laboratory; such rotation both improves mutual understanding of the requirements for research and speeds transfer of new technical information. These collaborations are intended to ensure that the Army knows and can work with the best and the brightest people elsewhere. The result is that the work is first class, and the Army technical staffs are able to adapt and help adopt these new developments for use in other sectors of the Army.

[1] Report of an Expert Panel on the Future of Army Laboratories, *Improving Army Basic Research* (Arlington, VA: RAND, 2012); Final Report of the Army 2010 Army Acquisition Review Chartered by the Secretary of the Army, *Army Strong: Equipped, Trained and Ready* (Washington, DC: Office of the Secretary of the Army, 2011).

The current Army S&T portfolio has seven segments:

- Basic Research
- The Soldier (nonmedical)
- The Soldier (medical)
- Ground
- Command, Control, Communications, and Intelligence (C3I)
- Air
- Enduring Technologies.

Each of these segments is subdivided into six or seven component programs. For this discussion, we classify the research in three categories: Army Unique, Army Shared, and Dominated by Others. *Army Unique* covers work that others have little or no motivation to work on and the subject matter is critical for the Service. In these circumstances, the Army maintains a robust research program in house benefiting occasionally from work done elsewhere. There will normally be a strong basic research component to ensure that the Army anticipates and is prepared for future developments in the technology and in threats involving that technology.

Army Shared includes research topics where both the Army and others are motivated to push the state of the art. Such topics include sensors, hardened electronics, and situational awareness on the battlefield. For these types of technologies, the Army has active research programs addressing specific applications important to the Army and where the work of others is not focused on Army interests. The Army work is tailored to meet specific requirements provided by the representatives of the warfighters. Long-term basic research is limited to these specific needs and to solving unanticipated problems that arise in the Research and Development program. In shared areas, various forms of collaboration are employed, ranging from informal cooperation on specific points to formal collaborations under contract agreements. The Collaborative Technology Alliances and the Collaborative Research Alliances fall in the latter category.

The third category, *Dominated by Others*, includes technology where the private sector or another part of the government is dominant and the Army relies on them for research. For example, in the development of new computers, the Army's role in research is to help the acquisition community adapt the technology to special needs of the warfighter. It is unlikely that there will be a long-term basic research program in this category.

Parsing the portfolio into these categories, however, is judgmental; people will differ about where to place a particular portfolio element. For example, the desire of the Soldier to see well at night led to the Army developing a dominant position in night vision technology. Army success produced market opportunities in the commercial sector so that, today, there is technical competence in industry as well. It is also true that, in fielding a technology such as night vision, industry has to learn how to manufacture the devices and components the Army needs. So there is expertise in various companies fostered by the Army. But the Army is maintaining its technical lead in night vision by developing and evaluating new concepts for next generations. Thus today both the Army and industry are competent in night vision technology, even though the Army will continue to press new developments.

Another example is in armor for the main battle tank. The armor for the Abrams tank grew out of some work done in the United Kingdom, the Chobham armor concept.[2] The Army was working on this in parallel with the British. Subsequently Army research added more modifications so that today Army armor leads the technology. Given the importance of survivability of the tank and its crew the Army is maintaining its research on armor and is pushing the limits wherever and however it can.

The situation with armaments is similar. The Army has always had technical programs to improve its weapons and holds the lead for many. The work at Benet Laboratory and Watervliet Arsenal has given the Army a strong position in developing and manufacturing large bore guns both for itself and for others in the military. There is no motivation for the private sector to develop cannon technology. Current problems being addressed are in manufacturing materials, material coatings, and in manufacturing processes. An example of the importance of solving these problems is that the dimensional precision and accuracy of a gun tube, along with its stability under sustained firing, contributes to the accuracy of the weapon. Research on the factors affecting these errors have been a major focus over the years, and are a special niche for the Army weapons research program. One solution to this problem was the development of GPS fuzes for artillery rounds to reduce the number of rounds needed to hit a target. However, it took time to create a fully functioning weapons system. Early models only showed the path of the round and where it would hit, while later efforts added guidance to the fuze ensuring a very large reduction in the impact error calculations. The result is the Excalibur artillery round, which has been fielded in Afghanistan. The design of the fuze is such that it can be screwed on to rounds in the current stockpile. This is an example of an “Army Unique” capability.

[2] Richard Chait, John W. Lyons, and Duncan Long, *Critical Technology Events in the Development of the Abrams Tank: Project Hindsight Revisited*, Defense & Technology Paper 22 (Washington, DC: Center for Technology and National Security Policy, December, 2005).

III. THE BASICS OF EVALUATING THE PORTFOLIO

The process of evaluating the portfolio may be done by internal staff at the office of the Deputy Assistant Secretary of the Army for Research and Technology, by others in the Army Secretariat, by the Office of the Secretary of Defense, or by external experts. In any case, the review should proceed somewhat as described in the following sections of this paper. A first step is to ask a series of questions such as the following:

- How does the work support the Army mission?
- What is the priority given to the area by TRADOC and Army leaders?
- Is the proposed technology essential or just nice-to-have?
- What is the projected impact? Compared to other Army S&T programs?
- What is the relation to forecasted trends in technology and in threats?
- Is the area within the scope of the Army's current programs? Is it within the expertise of the S&T staff?
- Can the Army develop collaborations with others already competent in the field?
- Can the private sector or other government entities provide the technology needed? If so, what and how much research would be needed to adapt their work to Army needs?
- What would the absence of Army in-house expertise mean to the warfighter?
- What is the Army's expertise in this area?
- What expertise exists elsewhere in the military or the private sector?
- Is the Army dominant in the field?
- What would happen if the Army were to stop research in this field? Are other sources ready and able to do the work? At what cost in time and money?
- Is the size of the Army program at a critical mass?
- Is the budget for personnel, facilities, and capital equipment adequate for the job?
- Are the necessary resources already on board (for a new project launch)?
- Is there provision for basic research to support the programs and ensure it is at the frontiers?
- How competent are Army personnel in this field as measured by publications, patents, recognition, etc. compared to other similar facilities?
- How will progress be assessed? Are there criteria for continuing or termination?

To elaborate, consider the following approach. The review package and briefings should have the Component Technical Areas and Technical Descriptors. The Descriptors would include technical products that fill desired capabilities, list the Army contributors and funding, and the stakeholders. The final section should address four major categories: the quality of the technical staff and the technical managers, the relevance of the program, alignment of the program with the Army mission and priorities, and consistency with Army forecasts of future developments in technology.

As an example, consider the area of C3I (Command, Control, Communications, and Intelligence), a technical area shared with industry.

- **Technical areas**: intelligence and electronic sensors, other sensors**,** communications, and mission command
- **Products**: sensors for: active/passive UV, visible, and Electro-Optical/Infra-Red; terahertz, mmw, radar, acoustic, magnetic, seismic, olfactory, and tactile sensors; sensor components, multisensors, sensor processing, and data fusion

- **Capabilities**: reconnaissance, intelligence, surveillance, and target acquisition (RISTA), navigation, pilotage, persistence surveillance, forensics, human intent and identification, health monitoring, early warning, missile seekers, and munitions guidance, detection of improvised explosive devices, countermine, chem./bio hazards, and robot perception under all weather conditions and terrains, and through walls.

Contributors

1. Communications and Electronics Research, Development, and Engineering Center: Night Vision and Electronic Sensors Directorate, Intelligence and Electronic Warfare Directorate
2. Army Research Laboratory: Sensors and Electron Devices Directorate, Communications and Information Sciences Directorate, Human Research and Engineering Directorate
3. Tank Automotive Research, Development, and Engineering Center
4. Armament Research, Development, and Engineering Center
5. Aviation and Missile Research, Development, and Engineering Center
6. Edgewood Chemical and Biological Center
7. Natick Soldier Research, Development, and Engineering Center
8. Corps of Engineering Research and Development Center

Customers

1. Program Executive Office (PEO) Aviation
2. PEO Ground Combat Systems
3. PEO Missiles and Space
4. PEO Soldier
5. PEO Chemical/Biological
6. PEO Command Control Communications-Tactical
7. Medical Research and Materiel Command
8. Training and Doctrine Command
9. Logistics Innovation Agency
10. Defense Threat Reduction Agency
11. Edgewood Chemical and Biological Center
12. Special Operations Command
13. Joint Improvised Explosive Devices Defeat Organization
14. Rapid Equipping Force
15. Department of Homeland Security
16. Department of Energy.

The data needed for evaluating the effort would be provided by the contributors and customers listed above.[3] The questions to be answered are, for example, those at the beginning of this chapter.

Some Preliminary Assessments

Ground and Air. The contents of the Ground portfolio suggest that most of those items are Army unique. Weapons, survivability, dealing with countermine/ improvised explosive devices and technical improvements to platforms are necessary for the warfighter. More effective sources of power, unmanned systems, and logistics are areas where the private sector has much to offer. Some, such as alternate fuels, are being addressed in very large programs by the U.S. Department of Energy. Subsequently, the Army should not invest heavily in this area except to adapt the findings to its needs. For the Air portfolio, the design and structure of helicopters is a shared area with industry. This is recognized in the Army's National Rotorcraft Technology Center where cooperation among the players is the norm. Most of the topics are of special interest to the Army; some are also of interest to the private sector. Examples of the latter are better fuel efficiency for the helicopter engines, lightweight drive trains, improved reliability and durability, and reduced weight and vibration. Unmanned aerial vehicles are a topic of the highest priority for the Air Force at the current time, and the Army will learn from their work and adapt it to its fleet.

C3I. Sensors, communications/computers, and command and control are essential items for the battlefield. Some will be specific to the Army, while others are of interest to the other services and to our military partners around the world. Everyone in and out of the military is interested in sensors. New developments in solid state physics continue to be made. The technology is moving to nano-scale devices. All of these influences will have an effect on future technology. Seen together, the impact on night vision, detectors for sensors on platforms of all types, and force protection warning devices will help improve the detection of movements, the launch of mortar shells, and sniper bullets on the battlefield. Communications and computer technology derive from the work of that industry.

Developments in computers are the province of industry, but software is another matter. Special programs are needed as real-time decision aids for battlefield commanders. Many technologies are needed for the gathering and analysis of intelligence information. The amount of data collected by today's satellites and surveillance aircraft is creating a need for better methods of mining and assessing this information in real- or near-real time. This is essential for today's Army and will be even more so in the near future. However, data mining is of great interest in other agencies and the private sector. Researchers in astronomy and in atmospheric science deal with very large amounts of data coming in everyday, sometimes every hour. Thus, research in this area should be left largely to those sectors. Techniques for the fusion of data from different sources are also needed. A need highlighted in Iraq is for devices that can reveal the contents of buildings either by seeing through the walls or by entering surreptitiously via micro-autonomous robots. Research in both approaches is active in the Army.

The Soldier. This portfolio is separated into two parts: one for nonmedical, the other for medical. The nonmedical section is divided into two subsections: the integration of humans with machines and measures of effectiveness regarding that integration, and how to improve the design of

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[3] For possible metrics, see Report of an Expert Panel on the Future of Army Laboratories, *Improving Army Basic Research* (Arlington, VA: RAND, 2012), 50–51.

equipment. Both these topics are of interest to many in and out of government because it is of pressing importance to soldiers on the battlefield and therefore there is justification for some work in the Army. Another area that has arisen recently is that of small unit operations. The Army is moving to a focus on independence in units as small as the squad. Studies are currently underway on communications within small units, as well as upward to high echelons. This has been and is especially important in operations in dense urban areas. The selection of Army warfighters and the training necessary to make them effective is always a priority. This includes finding ways to determine the toughness and resilience of new personnel to help improve their ability to surmount post-traumatic stress disorder and to maintain a high level of effectiveness on the battlefield. As this is far more prevalent in ground soldiers than members of other services, it may be of more importance to the Army than to other services.

Medically, survivability of the troops and care of combat casualties are perhaps the top priorities of Army commanders. Topics such as improved body armor for protection of the head to minimize traumatic brain injuries are important priorities for the Army Medical Command. Part of this is improving the resistance of soldiers to infectious diseases. On the battlefield, ways are needed to monitor the vital signs of soldiers as they work and after they are injured. Research is ongoing on fabrics for uniforms that perform monitoring while serving the usual functions of cloth. Better means of stemming hemorrhage have been developed during the Middle East conflicts. This is a top priority in treating wounded on the battlefield. Finding markers in blood that can signal internal damage in the brain or elsewhere is a dream of medical researchers. Currently sufferers from traumatic brain injuries may be undiagnosed until much later. The Army seeks a biological marker such that a simple blood test would reveal brain damage long before there would be visible symptoms; this would enable early diagnosis and treatment. It should be noted that there is, in the medical research program, a large amount of research that is not directly connected to the needs of the warfighter. A notable example is the DOD research on breast cancer, a program managed by the Army Medical Command’s Medical Research and Materiel Command (MRMC). Finally, the Army is funding academic consortia to develop organ regeneration science and technology. The ultimate aim is to help soldiers suffering amputations. A related technology is the control of prostheses by electronic connections to the nervous systems at appropriate levels. Some success has already been achieved with the Defense Advanced Research Projects Agency leading the way. The Army medical research program is closely linked to non-military medical research, including pharmaceutical, and depends on the community for various efforts required to achieve Food and Drug Administration approvals. Collaboration and cooperation is the rule.

Enduring Technologies Portfolio. The work on environmental quality at installations, including clean-up on ranges and at former dumps, is important for compliance with environmental rules and regulation. However Army research is relatively minor. Pollution is an issue that society in general shares. Disposal of chemical weapons has been and still is of major concern. Much of the research done in this area is engineering work, with analytical methods the subject of some study. These analytical methods are needed to ensure that not even the least amount of toxins is released during disposal.

Much of the Army’s physics-based modeling and simulation work is done on high performance computers. A principle source of such computing is provided by the High Performance Computing Modernization Program, now managed by the Corps of Engineers at Vicksburg. They manage centers of excellence across DOD. This does not involve research on developing better supercomputers; that is left to industry and academe. The centers provide the means to work on problems that are intractable on less capable computers. There is also very good work on network science for the battlefield that relates to work in the private sector and in academe.

Basic Research. We consider here three categories of basic research: in-house research, and two types of extramural research. The in-house research, conducted by Army technologists, may be long-term exploratory work pushing the frontiers, or relatively short-term study to elucidate phenomena raising barriers to progress on current projects. In neither case does the DOD definition of 6.1 research apply. Namely, the work is curiosity work with no specific application in mind. The two extramural categories include single-investigator grants, typically to universities, and sponsorship of large centers of excellence. These latter include, under the rubric of University Affiliated Research Consortia, two sets of programs called Collaborative Technology Alliances and Collaborative Research Alliances established by ARL and designed to bring together the external consortia members with in-house Army technical staff. (External centers of excellence are not so closely related to Army laboratories.)

ARL is the leader in Army basic research both in in-house work and, since the Army Research Office (ARO) is part of ARL, in extramural research. In recent years the amount of in-house basic research at ARL has been reduced by transferring 6.1 funds to the Collaborative Technology Alliances.

A lengthy study of basic research in the Army by the Office of the Deputy Assistant Secretary of the Army for Research and Technology is currently underway looking at the portfolio. In particular, the study is looking at the selection of basic research areas and the scenarios and technology gaps derived from the analyses of TRADOC. This study is focused on the grants made by ARO and will lead to a more formal articulation of the Office's philosophy and management approach. This study and a companion study of the formulation of the Army's applied research program will produce some revamping of the procedures and programs to make them more understandable to the warfighters and the Army's senior leadership.[4]

The Basic Research Portfolio. The basic research portfolio in the current analysis is in four component parts: platform centric; material centric; information centric; and human centric.

ARO sponsors research that is intended to push the frontiers of already state-of-the-art science and technologies, and to identify and pursue new areas of research that may be useful to the Army in the future. Projects in the sciences include study of new concepts in physics, chemical sciences, and materials, each covering a number of subareas that are at the frontiers of knowledge. The current summary of the portfolio supplied by the Office of the Deputy Assistant Secretary of the Army for Research and Technology is arranged by major topics, not by organization. Thus there is no mention of ARO's basic research in biotechnology, neuroscience, and other areas in life science now being pressed in the scientific community at large. A more detailed study would analyze these areas as well.

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[4] Dr. Marilyn Freeman, *The United States Army's Science and Technology (S&T) Program for Fiscal Year 2013*, Statement to the U.S. House of Representatives, Committee on Armed Services, Subcommittee on Emerging Threats and Capabilities, Second Session, 112th Congress, February 29, 2012, available at <http://defenseinnovationmarketplace.mil/resources/Freeman_Testimony_2013.pdf >.

ARO specifically excludes certain sub-branches of areas, although it does ensure some room remains available for unusual opportunities that could be useful for the Army:

> The Physics Division has little direct interest in relativity and gravitation, cosmology, elementary particles, nuclear physics, astronomy, or astrophysics, since they generally have little impact on the areas of Army needs. Nevertheless, the possible relevance of topics within these other physics disciplines is not absolutely discounted, and discussions of potential exceptions are welcome.[5]

An inspection of the science topics ARO is interested in reveals a broad range of research areas, each of which is related to some aspect of the Army's mission. ARO's Physics Division states:

> Condensed Matter Physics (CMP) is a foundational science enabling fundamental Army technologies in areas such as information processing, communications, sensors, optical components, electronics, optoelectronics, night vision, seekers, countermeasures, and many others. Technologies such as these would not exist today, at least not as we know them, without visionary research in the field of CMP. The ARO CMP program strives to continue this level of impact by looking beyond the current understanding of natural and designed condensed matter, to lay a foundation for revolutionary technology development for next generation and future generations of warfighters.[6]

The MRMC performs or sponsors basic research in many different areas. Recently it has established, with funding support from a number of other federal agencies, two research consortia in a number of universities on tissue and organ regeneration. Each of these civilian consortia is itself a multi-institutional network.[7] MRMC conducts programs on traumatic brain injury, blood loss control, pain management, and control of and immunization against a variety of infectious diseases that are hazards to soldiers. These last named programs are generally carried out cooperatively with the pharmaceutical industry and the Food and Drug Administration. MRMC has a long and notable history in developing and demonstrating techniques for combat casualty care on the battlefield and for subsequent long-term medical care and rehabilitation for wounded and traumatized soldiers.

The Corps of Engineers Engineering Research and Development Center has a number of basic research programs—many in environmental areas such as remote sensing of terrain—and it conducts modeling and simulation studies on its High Performance Computing Shared Resource Facility. The Engineering Research and Development Center also manages DOD's High Performance Computing Modernization Office. A group within this Office manages a program called CREATE that is "developing and deploying scalable, multiphysics-based computational

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[5] Army Research Laboratory, *Army Research Laboratory Broad Agency Announcement for Basic and Applied Scientific Research*, W911NF-12-R-0011, 15 May 2012 – 31 March 2017, 93, available at <www.arl.army.mil/www/pages/8/research/Final_Post_ARL_BAA_W911NF-12-R-0011.pdf>.

[6] Ibid., 93.

[7] *Armed Forces Institute of Regenerative Medicine*, homepage, available at <https://mrmc.amedd.army.mil/index.cfm?pageid=medical_r_and_d.afirm.overview>. One consortia is led by the Wake Forest University Baptist Medical Center along with the McGowan Institute for Regenerative Medicine at Pittsburgh; the other is led by Rutgers University, the State University of New Jersey, along with the Cleveland Clinic.

engineering tools to design and analyze DOD weapons system performance."[8] This is exploratory work pushing the frontier in a new area for DOD computing, namely, becoming involved directly in the engineering and manufacturing end of the acquisition timeline. The use of high performance computing in this way in the private sector is shown to shorten the time to complete new product development by as much as a factor of three.[9] This result is made possible by taking advantage of the power of these machines to model complex systems that have been beyond the reach of less powerful computers.

Portfolio Summary. The S&T portfolio is the result of many studies and decisions over many years. It has been revised and shaped by the changing needs of the warfighter, as well as continuing discussions between the S&T community and the warfighters as represented by TRADOC at policy levels. It also maintains contacts between members of the Army laboratory system and soldiers at home and abroad. TRADOC regularly issues the top Army challenges. The S&T program planners update their priorities accordingly and add new programs (and terminate older, lower priority work) to maintain alignment of the S&T programs with doctrinal priorities. For short-term work, the alignment must be very close. Programs in advanced development are tailored to respond to a list of 24 Army S&T Challenges.[10] Somewhat longer-range work in applied research anticipates the evolution of the problems. Long-term, basic research (6.1) seeks to uncover new opportunities at the frontiers of scientific and engineering knowledge. The Army has established centers of excellence in basic research and early applied work based on present needs, but with the flexibility to pursue new leads.

The following is a list of areas which, in our judgment, occupy a special niche in Army technology and therefore should receive priority support:

- Soldier and vehicle armor and armaments
- Night vision equipment
- Unattended ground sensors and sensor networks
- Air acoustic, seismic, and magnetic sensors
- Terrain and topographical analysis and navigation
- Soldier power and thermal management of platforms
- Helicopter protection and lethality
- Individual soldier health sensing and monitoring
- Individual soldier robotic associates
- Mobile ground communications networks
- Mine/IED detection and clearing at operational tempo
- Tactical chemical/biological/nuclear detection and protection
- Ground combat survivability/vulnerability analysis.

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[8] John W. Lyons, Richard Chait, Charles J. Nietubicz, *The Use of High Performance Computing (HPC) to Strengthen the Development of Army Systems*, Defense & Technology Paper 87 (Washington, DC: Center for Technology and National Security Policy, November 2011).

[9] Loren Miller, quoted in Council on Competitiveness, *Goodyear Puts the Rubber on the Road with High Performance Computing,* Case study, 2009, 4, Available at <www.compete.org/images/uploads/File/PDF%20Files/HPC_Goodyear_032009.pdf>.

[10] See *Army Science & Technology problems and Challenges*, PowerPoint, undated, available at <http://usarmy.vo.llnwd.net/e2/c/downloads/239849.pdf>.

IV. EVALUATING THE QUALITY OF THE PROGRAM AND ITS EXECUTION

The second part of the Army S&T program review by the Deputy Assistant Secretary of the Army for Research and Technology is seeking answers to the following questions:

- How does one assess the execution of the program with existing research staff and infrastructure?
- Do we have the best personnel and infrastructure compared to leading research and development programs?

In this section of the paper we develop a methodology for making these evaluations. We begin with a discussion of the factors that are necessary to achieve excellence in a research laboratory. Next is a review of the practice of expert review of the laboratory and its work by unbiased subject matter experts. We then consider the relevance of the work and the value of continued contact with customer and ultimate users of the results from the laboratories. We consider the need for and value of formal and informal collaborations with other laboratories. All of this discussion leads to the role of excellence in a laboratory to its standing in the community and to the support the laboratory has in the senior leadership in the Army and the authorizing and appropriating committees in the Congress.

The quality of a program of research and development depends on many factors, but the most significant are the quality of the research staff and of the management. Close behind are the quality of the facilities and capital equipment. According to a 1991 report to the Office of the Secretary of Defense, an effective laboratory will exhibit the following characteristics:

- A clear and substantive mission
- A critical mass of assigned work
- A highly competent and motivated work force
- An inspired, empowered, highly qualified leadership
- State-of-the-art facilities and equipment
- An effective two-way relationship with customers
- A strong foundation in research
- Management authority and flexibility
- A strong linkage to universities, industry, and other government laboratories.[11]

These statements however do not represent the whole picture. The laboratory program must be aligned with the vision and mission of the parent organization; in this case the U.S. Army. In the previous section we discussed the evaluation of the portfolio of the S&T program and pointed out that it is aligned with the needs of the warfighter through continuing discussions with the soldiers and their representatives. The quality of the S&T product depends on the relevance of the work to the needs not only of the soldiers but also of the initial customers of the work. For example the Army Materiel Command's corporate laboratory—ARL—works on problems defined by Army TRADOC, but delivers its results to intermediaries such as the Research, Development and Engineering Command and the Program Executive Officers and Program

[11] Charles E. Adolph, chairman, *Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories*, Report to the Secretary of Defense (Washington, DC: Department of Defense, September 1991).

Managers of the acquisition community. They can judge the immediate impact on their work. The ultimate impact, also a measure of quality, is harder to evaluate because there are many hurdles before the final product or process is fielded. Even when fielded, there may be many years of experience needed before conclusive appraisals can be made. Since the managers of S&T can't wait for years to discover how well they have done, they need some way of evaluating the work in the short term.

The evaluation of the execution of the program covers three phases: the planning stage, current laboratory work, and completed work. Planning involves evaluating proposals for new work and assessing them for relevance; the availability of qualified research staff including the project leader; the match to facilities and equipment on hand; the funding necessary to acquire additional resources if needed; and whether or not the challenge of the problem posed is such that it can be solved in a time frame that is practical for the warfighter. One measure of quality of the program is the extent to which the laboratory or laboratories are prepared for future demands; preparedness is a quality that requires foresight (and technology forecasting) and flexibility. The planning phase of the Army S&T program is conducted jointly with TRADOC and the S&T's customers for the 6.2 and 6.3 parts of the program. Recently TRADOC has become involved in the 6.1 program in terms of the coverage of the areas in the list of 24 Army priorities for S&T prepared by the Deputy Assistant Secretary of the Army for Research and Development in concert with TRADOC. Much of the planning exercise has been discussed in Section II on the portfolio.

Peer Review. Evaluation of the quality of current research and development work is somewhat more straightforward than evaluating the portfolio in that peer review is the prime evaluating tool. Currently, there is an established technique for peer review of laboratories which can aid in ensuring quality in research laboratories.[12] There are many variations—different laboratories may require different approaches. If the peers are drawn from within the laboratory or its parent, there will be good knowledge of the technical area and the challenges being addressed. However, internal judgments may be biased based on the stakes held by the evaluators. On the other hand, external evaluators will have less intimate knowledge of the specifics of the work but their evaluation will have more credibility. For most assessments, credibility is the leading characteristic as the results will help local management improve their work or even change course. For government laboratories, peer review processes will help in justifying budget documents. Conclusions from various studies of peer review of laboratories indicate that the best way to do this is as follows:

- Contract the evaluation to a recognized and respected entity such as the National Research Council of the National Academies.
- Have the contractor manage the entire process from picking evaluators, planning agendas, handling meeting logistics, and supervising preparation and distribution of reports.
- Appoint panels of evaluators that consist of independent subject matter experts with knowledge of the areas of interest.

[12] National Research Council, Panel for Review of Best Practices in Assessment of Research and Development Organizations, *Best Practices in Assessment of Research and Development Organizations* (Washington, DC: National Academies Press, 2012).

- Have panels evaluate not only the technical work presented to them, but also the quality of the technical staff, the quality of the facilities and equipment, and the adequacy of the resources provided.
- Seek to evaluate the culture of the laboratory and the role of upper management in hiring, promoting, and motivating and retaining the staff.
- Hold out-briefing sessions with the staff, prepare written reports, and indicate the panel's impressions of the follow-up actions by the laboratory on recommendations from the previous report.

Most Army laboratories carry out some form of peer review, but not all. The evaluations run the gamut from using contractors as described above to conducting strictly in-house assessments. It would be useful for all Army laboratories to consider some kind of independent peer review of current work. One model is the review of ARL. This is done by the National Research Council and follows the above recommended course of action. ARL reviews began in the 1990s and have been done regularly since. The evaluation reports are published by the National Research Council and are available on the Web site of the National Academies Press.

Completed Work: Metrics and Benchmarking. Some aspects of a laboratory can be assessed quantitatively and the results can be compared to those at other laboratories, preferably laboratories that are widely regarded as outstanding. Metrics may include a variety of topics: staff educational level, staff age distribution, number of archival publications per technical staff member, number of patents, number of external awards and other recognitions, elected memberships to honorary societies such as the National Academies, and so on.[13] Such metrics are useful as management tools, but caution must be taken in using them. These measures do not, of themselves, indicate the quality of the entries. As an example, a laboratory can have a number of unused patents and a string of uninspiring publications. In this situation, this laboratory would have met its criteria for metrics, but be performing poorly. In comparison, a laboratory could have written brief papers that have won Nobel prizes.[14] The quality of completed work as evidenced in publications, patents, and various prototypes for products can be assessed by sampling done by outside peers. This will ensure a mix of metrics and qualitative assessments, and provide a far greater and far more accurate representation of effectiveness.

Simultaneously, the Army can compare itself with other military laboratories to give a more meaningful assessment. The Naval Research Laboratory would be a prime example for such a comparison, provided the assessment used similar metrics. Other possibilities for comparative analysis include the nature of the portfolio, such as percentages of basic and applied research, the amount of work in which the laboratory is a world leader in the technology, and the focus on short-term vs. long-term work.

We recently have provided an informal report to the Deputy Assistant Secretary of the Army for Research and Technology in which we listed eight factors important for evaluation of quality of the S&T program. The factors include quality of staff; quality managers; peer review; relevance (inputs from customers and stakeholders); technology forecasting; leveraging; scientific or professional positions and the Independent Research & Development (IR&D) conducted by

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[13] Report of an Expert Panel on the Future of Army Laboratories, *Improving Army Basic Research* (Arlington, VA: RAND 2012), 50–51. This report lists 39 metrics for evaluating basic research.

[14] James D. Watson and Francis H. Crick, "A Structure for Deoxyribose Nucleic Acid," *Nature*, vol. 171 (1953), 37-38.

DOD contractors; and visibility of Army S&T. We compared our list against the list of metrics taken from a recent report from the RAND Arroyo Center.[15] The result is shown in Appendix A. The published list of metrics amplifies our seven fundamentals. There is no contradiction in the two lists.

Impact and Relevance—Relations with Customers and Stakeholders. A quality laboratory will know its customers and be close to its stakeholders to ensure it fulfills their expectations for relevance and timeliness. The laboratory should address the needs in the priority in which they are presented by the customers. As noted earlier, the Army laboratories deliver their research findings to a well-defined set of customers: namely, the acquisition community and the warfighter's representatives. An assessment of a laboratory should include discussions held with samples of these communities. One way to determine how well the laboratory is serving its customers is simply to invite representatives to research reviews and listen to their comments. Laboratories, which detail a portion of their staff to acquisition offices under matrix management, hold regular meetings with those Program Executive Officers or Program Managers to review progress. One possible technique is to poll customers via a ratings sheet followed by serious discussion of any area not given a fully successful grade.

As noted in the introduction, the stakeholders are the senior leaders of the Army, DOD, and the taxpayers as represented by the U.S. Congress. The opinions of senior Army and DOD leaders are usually made known by them to the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASAALT). To enhance relations with stakeholders, meetings and laboratory tours can be effective, but stakeholder schedules make visits very hard to arrange. The ASAALT and sometimes senior assistants to the principals can be persuaded to make visits and discuss issues. Congressional hearings are too formal and too brief for effective communication. However, congressional staffers are often interested in the details and enjoy making laboratory visits.

Taking Advantage of External Expertise. No laboratory can be at the frontiers of knowledge in every subject for which it is responsible. Therefore, it behooves the laboratory to seek out experts to learn what they know, to cooperate where feasible, and to enter into formal collaborations where justified. There is no place for insularity in today's technological world, save only for classified work. Assessors of a laboratory's work should ask the staff what other experts are working in this field. Who are the leaders? How does this laboratory compare? If the laboratory is not among the world's elite in a particular field—not working at the state of the art—then it should be in active contact with those who are. There should be cooperative programs and perhaps formal collaborations. If not, then the laboratory should exit the field. It is a measure of the quality of the laboratory management as to whether it is addressing these questions. Use of comparative metrics, noted above, can be helpful in benchmarking the work against others.

The quality of the preparedness of the laboratory for future demands is helped by a regular program of S&T forecasting. The laboratory should be looking ahead and comparing what it forecasts against what the demands on it are likely to be. Forecasting can be done in different ways. At the individual or small group level, one expects the local experts to have a good sense of where their disciplines are heading. At higher levels, such as the laboratory or its parent,

[15] See Report of an Expert Panel on the Future of Army Laboratories, *Improving Army Basic Research* (Arlington, VA: RAND, 2012).

forecasting is done in an organized fashion, perhaps on contract. Forecasts of individual sciences or technologies should be combined with cross-disciplinary and multi-disciplinary predictions. One concept is convergence forecasting in which mixed panels of experts in several potentially related disciplines work together to make predictions and suggest specific research programs.[16] Forecasting should be a recurring activity in a rolling manner such that any given area is looked at every 5 to 10 years. The Deputy Assistant Secretary of the Army for Research and Technology sponsored a very detailed forecast of all areas of interest 20 years ago.[17] Resuming forecasting is long overdue. Lack of a forecasting program is a factor in judging the overall quality of the S&T effort.

Quality of S&T and Its Reputation. The reputation of an S&T program governs, to a large extent, its ability to secure resources for existing and new programs. The most important audience is therefore the parent of the program and other stakeholders with a financial interest. Their impression of the laboratory is formed in part by the technical results, but also by comments from outside the enterprise from customers and other interested people. For the laboratories, in particular, external opinion has been a problem. Reputation is formed by the impressions given by publications, presentations, external awards and other public recognition, and press coverage. Nothing is as impressive as the receipt of a Nobel Prize. The Naval Research Laboratory has one; the National Institute of Standards and Technology has four, and the National Institutes of Health have received five. The Army has none. However, over the years ARO has provided support for research that produced 18 Nobel prizes. The Army does not have an individual member elected to one of the National Academies. In the recent past the Army has had one. These omissions are at least, in part, because the effort has not been made to publicize the technical work and to nominate staff members for prizes and awards. The Army has not done the public relations work necessary to keep the laboratories' work in the public eye. Compare this with the Naval Research Laboratory and its reputation, or Bell Laboratories, which continually educates the public on who invented the transistor. Some laboratories cooperate with authors writing books about their work and their history. Jon Gertner's recent best-selling book on the history of the Bell Laboratories has received rave reviews and is an example of this cooperation.[18] Could similar public relations efforts be carried out for Army S&T? In fact, it was attempted on the 50th anniversary of the introduction of the first general purpose electronic computer, ENIAC (Electronic Numerical Integrator and Computer). Creation of the ENIAC was funded by the Army's ballistics program at Aberdeen Proving Ground at the end of World War II.

Because of this lack of aggressive publicity, the reputation of Army S&T is not what it could be. This has led to lukewarm support for the Army's S&T budget, lukewarm even on the part of some senior Army leaders. At best, this problem produces more support for Army contracts and

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[16] John Lyons, Richard Chait, and Simone Erchov, ed., *Improving the Army's Next Effort in Technology Forecasting,* Defense & Technology Paper 73 (Washington, DC: Center for Technology and National Security Policy, September 2010); Douglas Kiserow et. al., *Report of an Army Workshop on Convergence Forecasting, Mechanochemical Transduction,* Defense & Technology Paper 95 (Washington, DC: Center for Technology and National Security Policy, July 2012).

[17] National Research Council, *STAR 21–Strategic Technologies for the Army of the Twenty-First Century* (Washington, DC: National Academies Press, 1992).

[18] Jon Gertner, *The Idea Factory: Bell Labs and the Great Age of American Innovation* (New York: Penguin Press, 2012).

grants than for in-house work. Sometimes this is appropriate, sometimes it is not. The Army should not hide its S&T quality. Instead, it should be its biggest promoter and justifier.

Quality Summary. This discussion is focused on the laboratory on the assumption that the quality of the S&T program as a whole would be, to a large extent, the sum of the individual parts. We have considered three aspects of laboratory quality: the planning phase, the current work in the execution of the plans, and the completed technical work. Planning includes the alignment of the plans with the mission of the laboratory and of the Army. A quality plan includes the availability of quality staff (and managers); availability of needed resources including budget, facilities, and equipment; the allocation of resources to a balance of short- and long-term research; and a regular program of technology forecasting to ensure preparedness of the laboratory for future developments in science and engineering and evolving trends in threats to the nation.

Some form of peer review should be used to assess current laboratory work. We believe the best approach is to contract for panels of independent, unbiased subject matter experts. These panels should be asked not only to evaluate the current research and development as presented by the staff doing the work, but should also be asked to review the status of the facilities and equipment. In the course of talking with the staff and walking through the laboratories and meeting with management, the panels can get an idea of its culture and the nature of the management personnel. Such panel reviews should be done for each sector of the laboratory every 2 to 3 years. The degree to which the research staff interacts with and is cognizant of the work of others in the field is an important factor in rating the laboratory. Various kinds of cooperation and formal collaborations with external expertise are a way to make sure that the laboratory is at the state-of-the-art level and is pushing the frontiers. Working with others is a good way to be prepared for future developments.

Completed work produces impacts on the Army. Results from the laboratory reach the warfighter through the efforts of many players including the technical work in the offices of Program Executive Officers and Program Managers in the acquisition community. Results may be transmitted directly to industrial firms that are preparing for manufacturing of the new products or using the new processes from Army research. During war time, some results obtained in the laboratory are transmitted though accelerated procedures directly to soldiers on the battlefield. Laboratory findings are summarized in publications and presentations and often result in awards and other forms of recognition. Satisfaction with the laboratories' work in terms of relevance, quality, and timeliness should be tested by regular sessions with customers and stakeholders.

Comparisons of the laboratory with other laboratories deemed to be outstanding can be made via benchmarking. In this approach various metrics can be obtained and comparisons made. These would include external recognition as well as items that can be counted, such as numbers of papers and patents, percentages of Ph.D.s, and so on. Reputation is important for a number of reasons, but the most fundamental is the impact a strong reputation will have on the ability to secure resources from year to year.

Questions to be asked when assessing the quality of a research and development organization should include:

- Is the work aligned with the mission and priorities?
- What is the level of education of the staff? (percentage of Ph.D.s)
- What is the average age of staff? (retention rate)

- Do the managers have experience at the laboratory bench? What is their reputation? How do they affect the culture?
- What is the nature of the basic or exploratory work? How much?
- How closely does the staff work with experts in other laboratories?
- What is the nature of cooperative work with outside laboratories? Does the laboratory have formal collaborations?
- What is the quality of the laboratory's products? (number of transitions of results to customers)
- For each technical staff member, what is the number of publications, internal reports, patents, and presentations?
- How is the staff recognized? (awards, elected memberships)
- What has been the impact of the program on warfighting? (retrospective studies)
- What is the state of the facilities?
- What is the state of capital equipment?
- What are the results of benchmarking against peer laboratories?

V. SUMMARY OF REPORT AND RECOMMENDATIONS

In this paper we focused on the existing portfolio as provided by the ASAALT Office. Our object was to provide a methodology for evaluating only this existing program. However, to make a complete assessment one would have to consider what topics are either not being addressed or not being addressed adequately. The answers would assist in reorienting the portfolio. It would have been of great assistance if the Army had a current version of the Army Science & Technology Master Plan.

We classified the work of the Army S&T program in three aspects: work where the Army is dominant in the technology, work where the Army shares the technical lead with the private sector, and areas where the private sector leads. The priority and nature of the research program varies with the category. The paper discusses some details of evaluating the portfolio and presents a list of questions, the answers to which would help. The evaluation of the current research work in executing the portfolio covers three phases: planning, execution, and completed work. This paper provides another list of questions for assessing the quality of the current work. We discuss the quality of the staff, how to perform peer review, consider relations with outside experts, and ask about cooperation and collaborations with others. The paper provides an approach to reviewing and evaluating the quality of the portfolio itself and the technical execution of the programs and projects.

We recommend:

- The Army resume publication of the Army Science & Technology Master Plan
- The Army evaluate the current S&T portfolio along the lines suggested herein.
- The review should identify areas that are underfunded (or overfunded) and suggest corrections.
- The review should attempt to identify areas of science and technology not included in the current portfolio but which should be included.
- The evaluation should make sure that every program is directly in support of the Army's mission and vision.

VI. APPENDIX

Appendix A includes eight fundamentals taken from a draft report by CTNSP[19] in a matrix with a series of metrics. The X's indicate the relevant items in the rows that match the elements in the column.

	S&T Quality Fundamentals							
Metrics	**Quality Staff**	**Quality Mgrs**	**Peer review**	**Relevance**	**Tech Fcstg.**	**Leverage**	**STs & IR&D**	**Visibility**
Distribution by S&T degrees, age distribution, and field of research	X	X						
Fellowship in professional societies	X							X
Membership in national academies or similar bodies	X							X
Other professional recognition (prizes and awards)	X							X
Breakdown by advanced degrees and scientific and engineering disciplines	X							
Refresh and turnover rate of staff	X	X						
Invited and keynote speeches	X		X					X
Vision: commonality of goals		X			X			
Funding level		X	X	X				
Consistency of funding levels		X	X					
Scientific reputation of research managers		X						X

[19] Private communication to the Deputy Assistant Secretary of the Army for Research and Technology, June 6, 2012.

	S&T Quality Fundamentals							
Metrics	**Quality Staff**	**Quality Mgrs**	**Peer review**	**Relevance**	**Tech Fcstg.**	**Leverage**	**STs & IR&D**	**Visibility**
Number of significant breakthroughs and inventions in the past 10 years		X		X				
Recruitment of high quality researchers	X	X	X					
Relevance for the enterprise		X		X				
Rainmaker: ability to influence sponsors/funders		X		X		X		
Selection process: subfields to invest and proposals. Support for external review of proposals and research		X	X	X	X			
Success in helping technology transfer		X	X					X
Portfolio view of research activities (balance between enhancement, extensions, new challenges in existing areas, new emerging areas)		X		X	X			
Criteria and assessment process for researchers and their career advancement	X	X	X					
Emphasis on peer-reviewed competition for basic research funding		X	X					

	S&T Quality Fundamentals							
Metrics	**Quality Staff**	**Quality Mgrs**	**Peer review**	**Relevance**	**Tech Fcstg.**	**Leverage**	**STs & IR&D**	**Visibility**
Specification of research process, score cards		X	X	X			X	
Administrative burden on researchers		X						
Mentoring of new employees	X	X						
Operational management		X			X	X	X	
Intellectual stimulation	X	X	X		X		X	
Unstructured activities	X	X					X	
Interactions with customers				X		X	X	X
Support for new ideas		X			X	X		
Lab facilities; computing environment	X	X						
Publications	X		X					X
Citation by others	X		X					X
Peer recognition	X		X					X
Patents	X		X	X				X
Citation of patents by others	X		X	X				X
Tech transfer to field	X	X		X				X
Long-term impact on users and funders				X				X