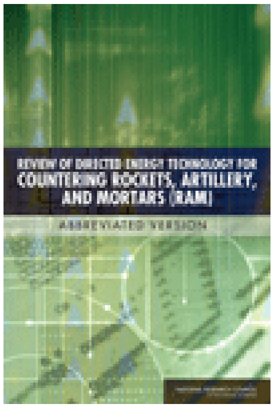

Review of Directed Energy Technology for Countering Rockets, Artillery, and Mortars (RAM): Abbreviated Version

Committee on Directed Energy Technology for Countering Indirect Weapons, National Research Council

ISBN: 0-309-11172-2, 42 pages, 6 x 9, (2008)

REVIEW OF DIRECTED ENERGY TECHNOLOGY FOR COUNTERING ROCKETS, ARTILLERY, AND MORTARS (RAM)

ABBREVIATED VERSION

Committee on Directed Energy Technology for Countering Indirect Weapons

Board on Army Science and Technology

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth St., N.W. Washington, DC 20001

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This study was supported by Contract No. W911NF-06-C-0184 between the National Academy of Sciences and the U.S. Army. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-11171-3
International Standard Book Number-10: 0-309-11171-4

Limited copies of this report are available from

Board on Army Science and Technology
National Research Council
500 Fifth Street, N.W.
Room 940
Washington, DC 20001
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Additional copies are available from

The National Academies Press
500 Fifth Street, N.W.
Lockbox 285
Washington, DC 20055
(800) 624-6242 or (202) 334-3313
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Printed in the United States of America

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COMMITTEE ON DIRECTED ENERGY TECHNOLOGY FOR COUNTERING INDIRECT WEAPONS

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Preface

Rockets, artillery, and mortars (RAM) have been mainstays of the world's military forces for hundreds of years. Historical approaches against RAM can be grouped as either purely defensive (e.g., taking cover in foxholes, bunkers, or armored vehicles) or offensive (e.g., attacking the launchers and guns). The U.S. military's approach to countering these weapons has primarily been one of counterbattery fire, which is consistent with traditional offensive strategies of taking the fight to the enemy.

The tactical calculus that favors one or the other of these approaches changes when the RAM targets are civilian populations rather than military formations and encampments. As illustrated in the fighting in southern Lebanon and northern Israel in 2006, the indiscriminate use of rockets and mortars against civilian populations, when combined with widespread press coverage, can turn low-cost tactical weapons into ones of strategic significance. Political pressures to stop attacks against civilians, even attacks that cause relatively little damage, can force major changes not just in tactics but also in the major strategic decisions on how and when to fight.

The need to defend civilians against RAM and the relative ineffectiveness of conventional counterforce approaches against irregular forces embedded in civilian populations imply that counterrocket, -artillery, -mortar (counter-RAM) technologies may be much more important to the United States and its allies than had been thought. A high-energy laser (HEL) system may be an attractive solution to this problem since, unlike kinetic approaches, a laser generates little or no collateral damage from debris. Recent advances in power scaling, thermal management, and efficiency, together with the short wavelength and inherently excellent beam quality, make solid-state lasers (SSLs) an attractive candidate for tactical weapons. This new application would bring with it new requirements, new opportunities, and new imperatives. As one example, a compact mobile defense system is needed to protect an army on the go, but civilian defense can certainly be provided by bulky, relatively immobile systems that are easier to realize. Other detailed system-level requirements such as coverage, range, and targets per minute may differ as well, with significant implications for technology readiness, resources required for development, and entry-into-service dates.

Altogether, an SSL weapon system that could counter RAM would be a tool of national importance. If one existed today, it would be in great demand in many places around the world. The value to the nation of such a strategic system adds to the value that accrues from existing requirements for the tactical defense of military formations and installations.

For decades the possibility has been raised that lasers could be used to defend strategic ground-based targets against offensive weapons launched at them; examples would be population centers or military-industrial complexes attacked by intercontinental ballistic missiles. More recently there have also been suggestions that lasers could be used in a theater of conflict to defend tactical military targets that are attacked by RAM, which have a shorter range. This more recent concept has the added significance of providing *strategic* defense if the target of the shorter-range attack is a population or government center in a more limited theater of conflict, such as in the Middle East.

This study focuses on the use of lasers to defend against rockets, artillery, and mortars, a mission labeled counter-RAM. Specifically, the U.S. Army is developing lasers that could be used as part of a defensive overlay of fixed installations. The technology under development employs solid-state laser devices, which use electricity to produce the laser beams, in contrast to the more mature laser devices, which use a chemical reaction to produce their beam and have already been tested for the counter-RAM mission. SSLs offer the advantage of eliminating dependency on an accompanying suite of chemicals in a tactical military environment. However, they require instead the transport of heavy equipment to generate the very large amount of electricity needed to operate the laser.

STATEMENT OF TASK

The U.S. Army Space and Missile Defense Command/Army Forces Strategic Command asked the National Research Council (NRC) to accomplish the study tasks listed below:

> Identify and provide recommendations concerning the quality and complementarities of the U.S. Army Space and Missile Defense Command/Army Forces Strategic Command (SMDC/ARSTRAT) and related technical efforts, including assessment of the effectiveness of DE Solid-state Laser (SSL) Weapon System Concepts in a counter rocket, artillery, and mortar (RAM) application. The following issues will be addressed:

- The assessment of technological maturity of each subsystem versus the level required for maturation of DE SSL Weapon System Concepts;
- The complementarities between the various pieces of the Army directed energy (DE) technology effort, including the solid-state laser device, the beam control/fire control element, and the system engineering/integration effort;
- The adequacy of the phenomenological base, including presently available data and ongoing research to validate the effectiveness against RAM targets of laser weapons with the envisioned characteristics;
- The credibility and adequacy of supporting technologies, including mobility and power generation/conditioning, being independently funded and developed by both the Army and others;
- The benefits which would accrue from maturation of related Directed Energy efforts at DARPA, other Services, DOE, or elsewhere;
- The sufficiency of Army budgets and allotted schedule to ensure adequate technological maturation and evaluation of a weapons prototype;
- The assessments of mission effectiveness of the DE SSL Weapon System Concepts; and
- The assessments of risk to overhead airborne and space platforms posed by DE SSL Weapon System concept.

To perform this task, the NRC established the Committee on Directed Energy Technology for Countering Indirect Weapons, informally called the Directed Energy Committee, in December 2006. The committee included experts in physics, high-energy lasers, mechanical and electrical engineering, systems engineering, electric power generation, fluid mechanics, program management, military operations, risk management, and technology integration and management (see Appendix A for biographies of the committee members). The committee operated under the auspices of the NRC's Board on Army Science and Technology (BAST).

Given that the committee would require access to classified national security information in the course of the study and that it would also require access to other information that is exempt from public disclosure under the Freedom of Information Act (5 U.S.C.§552, as amended by Public Law 104-231, 110 Stat. 3048), all members were required to have a Department of Defense security clearance.

The committee deeply appreciates the cooperation of the Army sponsor and the many government agencies and defense contractors that provided information during the conduct of this study. The committee is also very grateful to the dedicated staff of the NRC who worked tirelessly to assist the committee. Finally, the chair is especially thankful for the diligent efforts of the committee members, who completed this study under a rigorous time schedule. This report is the product of their efforts and represents a consensus view of the solid-state-laser technologies.

ROLE OF THE BOARD

The members of BAST, listed on p. vi, were not asked to endorse the committee's conclusions or recommendations, nor did they review the final draft of this report before its release. (Board members with appropriate expertise may nevertheless be nominated to serve as formal members of study committees or as report reviewers.) Established in 1982 by the National Academies at the request of the U.S. Army, BAST brings broad military, industrial, and academic experience and scientific, engineering, and management expertise to bear on Army technical challenges and other issues of importance to senior Army leaders. The board discusses studies that might be of interest; develops and frames statements of task; ensures proper project planning; suggests potential members of study committees, which are fully independent, ad hoc bodies; proposes reviewers of reports; and convenes meetings to examine and discuss strategic issues.

COMMITTEE ACTIVITIES

The first meeting for the committee was conducted near the headquarters of SMDC/ARSTRAT in Huntsville, Alabama. The second and third were conducted at the National Academies' Keck Center in Washington, D.C. The fourth and final meeting was conducted at the National Academies' Beckman Center in Irvine, California. (See Appendix B for dates and agendas.)

The committee received briefings from the following government agencies and defense contractors:

- U.S. Army Air and Missile Defense Battle Laboratory;
- U.S. Army Aviation and Missile Research, Development, & Engineering Center;
- U.S. Army Research Laboratory;
- U.S. Army Space and Missile Defense Command/Army Forces Strategic Command;
- U.S. Army Tank-Automotive Research, Development, and Engineering Center;
- U.S. Air Force Research Laboratory;
- Defense Advanced Research Projects Agency;
- Missile Defense Agency;
- BAE Systems;
- Boeing Missile Defense Systems;
- DRS-TEM, Inc.;
- Lockheed Martin Corporation;
- Northrop Grumman Corporation;
- Raytheon Corporation; and
- Textron Defense Corporation.

The months between the committee's last meeting and the publication of the report were spent gathering additional information, preparing the draft manuscript, reviewing and responding to the external review comments, editing the report, and conducting the required security classification review necessary to produce this Abbreviated Version of the report, which does not disclose information as described in 5 U.S.C.§552(b). It was mutually determined by the SMDC/ARSTRAT and the NRC that the full report might contain information as described in 5 U.S.C.§552(b) and therefore could not be released to the public in its entirety.

Millard F. Rose, *Chair*
Committee on Directed Energy Technology for Countering Indirect Weapons

Acknowledgment of Reviewers

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:

Thomas Ball, Naval Directed Energy and Electric Weapons Program Office;
R. Michael Dowe, Jr., Information Systems Laboratories;
William E. Howard III, Army Space and Strategic Technology Division (retired);
Edward Moses, Lawrence Livermore Lincoln Laboratories;
F. Robert Naka, CERA, Inc.;
Malcolm O'Neill, Lockheed Martin Corporation (retired);
Quentin E. Saulter, Air Force Research Laboratory/Directed Energy;
Edl Schamiloglu, University of New Mexico;
John T. Schriempf, Naval Directed Energy and Electric Weapons Program Office; and
John C. Sommerer, Johns Hopkins University Applied Physics Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recom-

mendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Harold K. Forsen, Bechtel Corporation (retired). 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 committee and the institution.

Contents

Summary

This study report was prepared by the National Research Council's Committee on Directed Energy Technology for Countering Indirect Weapons. The report provides results of the committee's assessments and committee recommendations concerning the U.S. Army's efforts to develop and demonstrate a high-energy, solid-state laser weapon system that could be used to defend an area a few kilometers in diameter against incoming rockets, artillery, and mortars (RAM). Specifically, as requested by the Army's Space and Missile Defense Command/Army Forces Strategic Command, the committee considered the quality and complementarities of the Command's laser program and related technical efforts in counter-RAM applications.

In performing this task, the committee addressed several issues, including the effectiveness of solid-state laser weapon system concepts, the technological maturity of various optical subsystems of the laser itself, and risk to overhead airborne and space assets. The committee also considered complementarities of various pieces of the technology effort, related systems engineering and integration, and the adequacy of related supporting technologies (such as power supplies and thermal management). It also evaluated the adequacy of the phenomenological base. Finally, the committee considered benefits that could accrue from maturation of related technical efforts outside the Army and the sufficiency of Army budgets and schedules to ensure adequate technological maturity and to evaluate a weapons prototype. The full statement of task is given in the report's preface.

OVERARCHING FINDINGS AND A RECOMMENDATION

The Army's development program is aimed at demonstrating a mobile 100 kilowatt (kW) solid-state laser weapon system concept that has the potential of performing usefully against RAM attacks. It is clear that the various pieces required to demonstrate a mobile 100 kW solid-state laser weapon system have relatively low technological maturity and relatively high risk and involve challenging engineering and integration issues. For this reason a transportable, rather than mobile, system was also considered. For a technology-paced program of this type, it is likely that substantially more money than the Army currently has programmed will be required to realize the demonstration. Indeed, the committee estimates that over the period of the program $100 million more than the amount currently planned will be needed.

The rudimentary effectiveness assessments made during this study reveal the clear benefits of higher laser power than is provided by the 100 kW demonstrator to counter more stressing raids and hedge the need to destroy future hardened RAM projectiles.[1] Accordingly, the committee endorses the Army's longer-term goal to eventually develop and field a multi-hundred kW solid-state laser (e.g., a 400 kW laser weapon system).

In addition to assessing the Army's current technology-paced program to demonstrate a 100 kW system, the committee examined a three-element sequential program of the committee's own design that could proceed as follows:

1. Early on, ruggedize and integrate into a transportable or mobile test-bed a previously developed, good-beam-quality 25 kW solid-state laser to demonstrate the ability to use laser technology of this type under realistic field conditions rather than in the laboratory. This test-bed would primarily reduce the development, engineering, and integration risks in spiraling to the 100 kW and 400 kW demonstrations and very likely pay for itself.
2. Proceed with a 100 kW demonstrator, only at reduced risk and cost compared to the current Army program because of lessons learned and data gathered with the 25 kW test-bed; the 100 kW demonstrator would also likely give the Army some useful military capability.
3. Fully fund the continuing longer-term 400 kW effort to follow the 100 kW demonstration; the 400 kW laser, which could be tested by 2018 under this sequential program, would offer much greater military effectiveness.

The committee's coarse estimate of the cost of the above sequential program is approximately $470 million. This kind of program would provide early and frequent opportunities for testing and evaluation as well as clear decision points

[1]Although the ultimate goal of the Army is a multikilowatt system, that does not mean that a 100 kW demonstrator will have no credible weapons capability or that it is not useful militarily. The 100 kW lasers could do some useful things, and 400 kW lasers could do even more.

for off-ramps if needed. Its major drawback is the higher peak funding required during the 3-year period when it must proceed in parallel (about 20 percent more in FY 2011 through FY 2013 compared to the Army's current development plans for the 100 kW system and a multi-hundred kW system). This program allows the Army to choose between higher middle-program development costs or increased program risks.

Recommendation: The Army should consider changing its high-energy laser technology development and demonstration program to reflect the three-phase (25 kW, 100 kW, and 400 kW) spiral approach of the proposed sequential program.

OTHER KEY FINDINGS AND RECOMMENDATIONS

Effectiveness estimates were briefed to the committee during this study. The committee's own assessments, although necessarily limited because of the time frame of this study, revealed several aspects of effectiveness that need thorough analysis to better illuminate the military utility of future high-energy lasers as the Army's high-energy laser technology development and demonstration program proceeds.

Recommendation: The Army should perform a detailed, quantitative study of the effectiveness of high-energy, solid-state laser weapon systems against future threats. That study should address a comprehensive range of parameters and issues, including various power levels (e.g., 100 kW and 400 kW), the effects of obscurants, weather, atmosphere (including turbulence with and without adaptive optics, scattering, and absorption), resistance to countermeasures that would increase the hardness of incoming RAM, and deployment tactics, concepts of operation, and associated training.

With respect to the maturity of various laser approaches, the committee developed Table S-1, which summarizes its assessments.

Although the committee identified ceramic slabs as the most promising near-term technical approach for solid-state lasers, other approaches hold promise over the longer term. Since laser efficiency is the single most important determinant of overall weapon size, a very significant improvement in efficiency over that demonstrated to date is required for a single-vehicle, mobile,[2] high-power laser system to be feasible.

Recommendation: The government should continue to pursue several competitive approaches for solid-state lasers for the next few years. The Army should

[2]The committee was briefed on single-vehicle (mobile) concepts, but none involved shoot-on-the-move capability. A transportable system involves one or more large trucks and relatively long set-up times.

TABLE S-1 Status and Committee Assessment of Various Laser Approaches

Technology/Advocate	Key Issues	Comments	TRL	Risk Estimate
NGST coherent beam combining amplifier chains, slab	Coherent beam combining complexity	Improve efficiency Complexity leads to system issues	TRL 4	Medium
Textron thin Zag, slab	Thermal lensing Low efficiency Thermal management Ceramic materials technology	Thermal lensing will require adaptive optics Complexity leads to major system issues Unstable resonator not-yet-proven approach	TRL 3	Medium to high
DOE/LLNL heat capacity, slab	Heat capacity limited BQ not stable Difficult thermal management issues	System concept requires multiple slabs with complex loading system and thermal management system	TRL 3	High

DARPA/HELLADS, slab	Thermal management with index-matched coolant BQ Optical efficiency	Lasing media are thin slabs with index-matched coolant flow between slabs To maintain index-match, laminar flow necessary Specific power difficult to maintain	TRL 3	High
Thin disk	Poor BQ at high power Thermal shock in gain media Difficult to scale to high power levels	Promises high efficiency Problems with coupling and beam combining expected	COTS, TRL 9 Other, TRL 3	High
Optical fiber, single mode	Single fiber limited Nonlinearities limit power scaling	Coherent and incoherent beam combining	TRL 2	High
Optical fiber, multimode	BQ	Difficult to propagate long distances due to poor beam quality	COTS, TRL 9	High

NOTE: TRL, technology readiness level (see Appendix D for more information); BQ, beam quality; HELLADS, High Energy Liquid Laser Area Defense System; NGST, Northrop Grumman Space Technology.

concentrate on a transportable system until efficiency is improved sufficiently to allow for a mobile system.

The committee's consideration of necessary supporting technologies revealed that thermal management will be a substantial part of the total mass and volume of a high-energy laser weapon system; thus, complete system designs that include all aspects of the supporting technologies (e.g., total system weight, volume, power) are necessary to ensure truly mobile systems. Hybrid electric power systems being developed by the Army have ample energy but currently lack sufficient power capability for solid-state laser weapon systems; also, the hybrid-electric timelines do not match those of the laser development and demonstration program. Ruggedization will be a key issue for 100 kW transportable and mobile systems and will require intensive engineering.

Recommendation: A transportable system should be implemented first, and complete system designs should be ensured for follow-on mobile systems. Army capabilities in power, energy, and thermal management should be utilized and interfaced with the laser program. To reduce risk for the 100 kW system and a higher power follow-on, ruggedization should be demonstrated early on at a lower power level.

Systems engineering and integration for a solid-state laser weapon system must be comprehensive, encompassing all aspects of all pieces of the system and their numerous interfaces. The current acquisition approach by the Army has made the government the de facto system engineer and integrator through the first phases of the High Energy Laser Technology Demonstrator effort, yet there is no evidence that the Army has established an organization or hired people to accomplish this critical function.

Recommendation: The Army should establish a systems engineering and integration team to develop the top-down performance allocations, error budget tracking, engagement timeline management, and integration plans for the high-energy laser system.

Valuable lessons can be learned from the Tactical High Energy Laser (THEL) program. The approach to testing and diagnostics is also important.

Recommendation: THEL lessons learned should be widely distributed and taken into account in the solid-state laser programs. The Army should establish a team to ensure that necessary systems engineering and integration functions are accomplished, and the approach for testing and diagnostics should be defined.

Adequacy of the phenomenological database is critical for a laser weapon system. A key characteristic is lethality (in other words, hardness, or the amount of laser energy per unit of surface area that is needed to destroy or disable an incoming projectile). The ability to destroy RAM targets by a laser depends on many factors, such as engagement geometry and the type of munition as well as the laser wavelength and dwell time on the incoming round.

Recommendation: Current efforts to characterize lethality at the solid-state laser wavelength should be pursued aggressively, and robust modeling and simulation under a range of threats in a variety of conditions, including potential countermeasures, should be undertaken.

The committee found substantial benefits for the Army's solid-state laser weapon system program from other programs outside the Army (e.g., ceramic materials in Japan, progress on diode arrays by DARPA and Lawrence Livermore, low-absorption-loss coatings in the United States and Europe, power electronics by the Navy and DARPA, and advanced energy storage by U.S. and Japanese companies).

Recommendation: The Army should continue to support research and development in advanced ceramics materials for lasers. The Army should also continue participation in U.S.-based and international research on various other elements of high-energy lasers, including related equipment for mobile laser systems (e.g., energy storage).

The use of lasers necessarily raises concerns about the safety of airborne platforms that may be in the vicinity, of any manned or unmanned spacecraft that may be in the laser's field of view, and of persons either on the ground or in the air who might suffer ocular damage from exposure to direct or scattered laser light. In all of the above situations, the probability of illumination is small, but the consequences could be significant. Risk assessments must take into account both probability and consequences, and deconfliction between laser firing and local airborne platforms must be included in the weapon system's battle management.

Recommendation: The Army should study eye safety for military operators and for civilians (collateral damage) and integrate the results into its development of concepts of operation. Predictive avoidance for space platforms should also be incorporated into the laser weapon system's battle management. The Army should start with the predictive avoidance approach of the Airborne Laser Program and should work with the operational communities and U.S. satellite agencies to establish rules of engagement for the laser weapon.

Appendixes

Appendix A

Biographical Sketches of Committee Members

Millard F. (Frank) Rose, *Chair*, is vice president for research and chief technical officer, Radiance Technologies, Inc. Prior to joining Radiance Technologies, he was director of the Science Directorate at the NASA Marshall Space Flight Center. Previous positions within the scientific community were the following: deputy director, Space Sciences Laboratory, NASA Marshall Space Flight Center; director, Space Power Institute, and professor, electrical engineering, Auburn University; and senior research scientist, Naval Surface Warfare Center. He has had a distinguished career involving progressively more responsible experience in performing and managing basic and applied research in the physical sciences and advanced technologies associated with space, shock wave physics, energy conversion, electronic warfare, directed energy technology, and space power technology. He has broad experience in planning, programming, coordinating, and implementing interdisciplinary R&D programs and received international recognition in the field of advanced power technology and space environmental effects. He is one of the few investigators who have published in the field of vector inversion generators. He is a fellow of the IEEE, an associate fellow of the AIAA, and a national associate of the National Academies. He was associate editor of the *Journal of Propulsion and Power* for 6 years and has been guest editor for several technical journals. He is the author/editor of five books, most dealing with high-power, high-speed phenomena; is the author of 160 technical papers in the open literature; and holds 12 patents, mostly in the area of advanced energy conversion. He is a past member of the NRC Board on Army Science and Technology and in that capacity participated in numerous BAST studies. He is a past member of the Scientific Advisory Board for the Sandia National Laboratories. Dr. Rose holds a certificate in electrical engineering from the Clinch Valley

College of the University of Virginia, a B.A. in physics from the University of Virginia, an M.Sc. in engineering physics, and a Ph.D. in engineering physics from Pennsylvania State University.

Rettig P. Benedict, Jr., is the current chairman of the Schafer Corporation board of directors. He is also the vice president for special programs and is responsible for business development and fulfillment in a wide range of programs relating to space capabilities and directed energy technologies with prime contractors and directly with the government. Dr. Benedict serves on several government advisory groups, including the ABL independent review team. Last year he was the study director for the AFRL Defensive Counterspace Study. He has also served on an NRC committee that studied directed energy testing. Dr. Benedict is on the board of directors of the Directed Energy Professional Society and serves as the treasurer. Prior to joining Schafer, Dr. Benedict was director, Space Defense and Surveillance, DCS Plans, Air Force Space Command in Colorado Springs, Colorado, from 1984 to 1988. In this capacity, Dr. Benedict was responsible for requirements development and advocacy, acquisition management, and implementation of all aspects of space surveillance and space defense. He developed ASAT requirements and established the ASAT force mix concept. He managed the Space-Based Radar requirements development, Ballistic Missile Defense planning activities, and participated in TENCAP planning. He was responsible for Space Defense Operations Center (SPADOC) upgrades in Cheyenne Mountain. Dr. Benedict was a key participant in Strategic Defense Architecture 2000 and Project Forecast II and an advisor to the Air Force Science Advisory Board. From 1979 to 1984, Dr. Benedict was assigned to the Defense Advanced Research Projects Agency (DARPA) as program manager of the Short Wavelength Laser Program. Dr. Benedict managed and technically directed broad programs focused on developing laser and beam control technologies for three DOD missions: Submarine Laser Communications (blue-green lasers); Ground-Based Laser ASAT; and Ballistic Missile Defense. He managed the evolution of high-energy electron beam pumped excimer lasers; free electron lasers; long-life, high-repetition-rate discharge pumped excimer lasers; early diode pumped solid-state lasers; and advanced atmospheric compensation technologies. Many of these programs were transferred to SDIO in 1984, where the research continued. Dr. Benedict holds a Ph.D. in physics from the Air Force Institute of Technology.

Robert L. Byer, NAE and NAS, is currently a professor of applied physics at Stanford University and has conducted research and taught classes in lasers and nonlinear optics there since 1969. He has made numerous contributions to laser science and technology, including the demonstration of the first tunable visible parametric oscillator, the development of the Q-switched unstable resonator Nd:YAG laser, remote sensing using tunable infrared sources, and precision spectroscopy using coherent anti-stokes Raman scattering (CARS). His current research includes the development of nonlinear optical materials and laser diode pumped solid-state laser sources for applications to gravitational wave detection and to laser particle acceleration. Dr. Byer is a fellow of the Optical Society of America, the Institute of Electrical and Electronics Engineers (IEEE), the American Physical Society, the American Association for the Advancement of Science, and the Laser Institute of America. In 1985, Dr. Byer served as president of the IEEE Lasers and Electro-optics Society. He was elected president of the Optical Society of America and served in 1994. He is a founding member of the California Council on Science and Technology and served as chair from 1995 to 1999. He has served on the Engineering Advisory Board of the National Science Foundation. At Stanford University, he was chair of the Applied Physics Department from 1981 to 1984 and from 1999 to 2002; associate dean of humanities and sciences from 1985 to 1987; vice provost and dean of research from 1987 through 1992; and director of the Hansen Experimental Physics Laboratory from 1993 to 2006. He is currently the co-director of the Stanford Photonics Research Center and the director of the Edward L. Ginzton Laboratory at Stanford. He served on the AFSAB from 2002 to 2004. He is a member of the National Ignition Facility advisory committee at LLNL, a member of the scientific advisory committee for the Linac Coherent Light Source at SLAC, and a past chair of the external advisory board for the Center for Adaptive Optics, Santa Cruz. Dr. Byer was elected to the National Academy of Engineering in 1987 and to the National Academy of Sciences in 2000.

Gregory H. Canavan is a senior fellow and scientific adviser at Los Alamos National Laboratory. He is also a fellow of the American Physical Society. His current research includes stochastic processes, data mining, and missile defense. Dr. Canavan is a member of the Missile Defense Agency advisory committee and the Army Science Board and has participated on several science boards and groups, including the USNORTHCOM Independent Strategic Assessment Group (ISAG), the U.S. Air Force Space Command Independent Strategic Assessment Group, the Defense Science Board Task Force on Missile Defense, the New York City Mayor's Commission on Counter Terrorism, the International Space Station Independent Cost and Management Evaluation Commission, and the American Association for the Advancement of Science. Dr. Canavan has consulted on a number of panels, including these: the DARPA Directed Energy Panel, the Defense Threat Reduction Agency Graybeard Panel, the Missile Defense Agency Senior Advisory Group, the Defense Policy Board, the NASA Earth Systems Science and Applications Advisory Committee, the Air Force Scientific Advisory Board, the National Academy of Sciences Committee on Global Climate Research, and the White House Science Council Military Panel. He has held previous positions as director, Office of Inertial Fusion, Department of Energy; special assistant to the Chief of Staff, U.S. Air Force; White House Fellow; Office of Energy Policy and Planning program manager; and is a retired colonel in the U.S. Air Force.

Dr. Canavan holds a Ph.D. and an M.S. in applied science from the University of California, Davis; an M.B.A. from Auburn University; and a B.S. in mathematics from the U.S. Air Force Academy.

Alan H. Epstein, NAE, is currently the R.C. Maclaurin Professor of Aeronautics and Astronautics and the director of the Gas Turbine Laboratory at the Massachusetts Institute of Technology. His responsibilities include teaching and research in propulsion, power production, heat transfer, fluid mechanics, flow diagnostics, and microelectromechanical systems (MEMS). He has been an active consultant to industry and government for more than 30 years, during which his activities included gas turbine design, system testing and advanced instrumentation, power systems, military infrared systems, and vehicle observable technology. He has won several international awards for heat transfer, turbomachinery, instrumentation and controls, and gas turbine technology. He is a member of the NRC Board on Army Science and Technology and the NRC Standing Committee on Technology Insight-Gauge, Evaluate and Review (TIGER). He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA) and of the American Society of Mechanical Engineers (ASME). He received his B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology in aeronautics and astronautics.

Alec D. Gallimore is the Arthur F. Thurnau Professor of Aerospace Engineering at the University of Michigan, where he directs the Plasmadynamics and Electric Propulsion Laboratory. Professor Gallimore is also an associate dean of the Horace H. Rackham School of Graduate Studies, where he oversees the graduate portfolio of 30 departments in engineering, the physical sciences, and mathematics. Professor Gallimore is also on the faculty of the applied physics program at the University of Michigan, is the director of the NASA-funded Michigan Space Grant Consortium, and is project director of the NSF-funded Michigan AGEP Alliance. He received his B.S. in aeronautical engineering from Rensselaer Polytechnic Institute and his M.A. and Ph.D. degrees in aerospace engineering from Princeton University. His primary research interests include electric propulsion, plasma diagnostics, space/reentry plasma simulation, and nanoparticle physics. He has experience with a wide array of electric propulsion technologies, including Hall thrusters, ion engines, arcjets, and MPD thrusters, and has implemented a variety of probe, microwave, and optical/laser plasma diagnostics. The author of nearly 200 journal and conference papers on electric propulsion and plasma physics, Professor Gallimore has been the recipient of a number of University of Michigan prizes, including the Trudy Huebner Service Excellence Award in 2005, the Harold R. Johnson Diversity Service Award in 2005, and the Outstanding Accomplishment Award in Aerospace Engineering in 2002. He received the Best Paper in Electric Propulsion Award for work presented at the 1998 Joint Propulsion Conference and the Outstanding Achievement in Academia Award from the National GEM Consortium in 2004. Professor Gallimore has graduated

17 Ph.D. students and 11 M.S. students. He serves on the American Institute of Aeronautics and Astronautics (AIAA) Electric Propulsion Technical Committee and is an associate fellow of AIAA. Professor Gallimore is an associate editor for the *Journal of Propulsion and Power* and has served on a number of advisory boards for NASA and the Department of Defense, including the United States Air Force Scientific Advisory Board (AFSAB). He was awarded the Decoration for Meritorious Civilian Service in 2005 for his work on the AFSAB. He is cofounder and CEO of ElectroDynamic Applications, Inc., a small, high-tech aerospace firm in Ann Arbor, Michigan, that specializes in electric propulsion.

Narain G. Hingorani, NAE, is an independent consultant who retired from EPRI following a 20-year career, including the last 5 years as vice president of electrical systems. Prior to joining EPRI, Dr. Hingorani spent 6 years at Bonneville Power Administration; his responsibilities included the commissioning of the Pacific HVDC Intertie and Series Capacitor compensation. He has helped many utilities in the specifying, purchasing, and commissioning of HVDC and the application of power electronics. At present, Dr. Hingorani provides consulting services to ONR, DARPA, and utilities in the area of development and application of power electronics and devices for transmission, distribution, industrial power, and marine power systems. Dr. Hingorani is credited with originating the concepts of flexible AC transmission system (FACTS) and custom power, which are expected to revolutionize future AC power transmission and distribution systems, respectively. He has authored over 150 papers and articles on HVDC and AC transmission and co-authored two books, one on HVDC power transmission (1960) and the other on flexible AC power transmission (1999). Dr. Hingorani received a B.Sc. degree in electrical engineering from Baroda University in India and M.Sc., Ph.D., and Doctor of Science degrees from the University of Manchester Institute of Science and Technology in England. In 1985, Dr. Hingorani received the Uno Lamm Award of the IEEE Power Engineering Society for outstanding contributions in high-voltage, direct current technology; in 1995, he received the 1995 IEEE Lamme Gold Medal for leadership and pioneering contributions to the transmission and distribution of electric power, and in 2005 received the Benjamin Franklin Institute Bower award and prize for achievement in science. In 2004, the IEEE Power Engineering Society decided to name its FACTS and Custom Power Awards the Nari Hingorani FACTS Award and the Nari Hingorani Custom Power Award, in recognition of Dr. Hingorani's pioneering work in these technologies. He is a life fellow of IEEE. In 1988, Dr. Hingorani was elected to the National Academy of Engineering. From 1988 to 1996, he was chairman of CIGRE Study Committee 14: DC Links and Power Electronics. From 1998 to 2004, he was a member of the IEEE Foundation Board. From 2002 to 2006 he served on the NRC Panel on Sensors and Electron Devices, which reviewed the Sensors and Electron Devices Directorate (SEDD) of the Army Research Laboratory (ARL).

Carol Livermore is currently the SMA Assistant Professor of Manufacturing in the Department of Mechanical Engineering at the Massachusetts Institute of Technology. Prior to joining that department, she was a research scientist in the Microsystems Technology Laboratories at MIT. Her present activities include teaching and research in the areas of mechanics, microelectromechanical systems (MEMS), and manufacturing techniques for micro- and nanoscale systems. Dr. Livermore's past and present research areas include high-power MEMS for portable power applications, high-efficiency chemical lasers based on MEMS components, self-assembly technologies for micro- and nanoscale systems, and quantum devices. Dr. Livermore was the technical program co-chair for ARL's 2003 Annual Symposium of the Collaborative Technology Alliances Power and Energy Program and served on the Technical Program Committee for PowerMEMS 2006. Professor Livermore received an NSF Career Award in 2007 and has over 25 publications in the fields of nanoelectronics, self-assembly, and the design and fabrication of MEMS. She holds an A.M. and a Ph.D. in physics from Harvard University and a B.S. in physics from the University of Massachusetts, Amherst.

Madeleine L. Naudeau is a senior member of the technical staff at Sandia National Laboratories, where she is part of the Directed Energy Laser Applications group. Her current work includes investigations into the nonlinear interactions of high-intensity lasers with a variety of materials (solids and air) for several programs of national interest. Dr. Naudeau received a Ph.D. in physics in 2002 from the University of Michigan in Ann Arbor, where she worked at the Center for Ultrafast Optical Science. For her thesis work she studied wavepacket behavior in atomic and excitonic systems using ultrashort-pulse laser (USPL) systems. Upon graduation, she joined the Naval Surface Warfare Center in Crane, Indiana, and was instrumental in initiating a program to develop new technology using novel lasers for countermeasures against MANPADS and similar threats.

George W. Sutton, NAE, graduated from the California Institute of Technology with a Ph.D. in mechanical engineering and physics. He currently works for SPARTA, Inc., where he has been instrumental in providing guidance for and reviews of new concepts for ballistic missile defense and the initiation of advanced systems for advanced sensors and weapons for ballistic missile defense. He is also a member of the laser technology team. Prior to joining SPARTA, Inc., Dr. Sutton was a principal engineer with ANSER (a not-for-profit corporation), where he was a member of the SETA team for BMDO for interceptor technology and high-energy lasers. He performed and published original analyses of aero-optical performance of externally cooled windows, uncooled optical dome and window thermal radiance, stresses, and optical aberrations; discrimination capability of one-, two-, and three-color passive optical and laser measurements; interceptor testbed flight test planning; testing techniques for image-motion compensation for strap-down seekers; performance of various infrared imagers for target acquisition; and supported the space-based laser project. From 1992 to 1996, he was director of the Washington office and chief scientist for Aero Thermo Technology, Inc. Dr. Sutton was a member of the SETA team for BMDO theater ballistic missile interceptor technology, concentrating on aerothermochemistry, aero-optics, and structures for BMDO hit-to-kill ballistic missile interceptors. He wrote original interceptor flyout computer programs for window heating, window emission noise, and target signal-to-noise ratio. He also wrote original computer program for end-game guidance and control to determine seeker resolution and accuracy effect on miss distance. Before that he worked at the Avco-Everett Research Laboratory on gasdynamic lasers (a name he coined), electric carbon dioxide lasers, and excimer lasers. Dr. Sutton modeled laser beam propagation through atmospheric turbulence with molecular absorption and fog/clouds. He also modeled the distortion of laser mirrors due to absorbed irradiance and modeled and performed experiments on material damage. He performed laser systems studies and wavelength optimization, including propagation and threat lethality using statistics on atmospheric turbulence, absorption, and fog. Prior to that, he worked at Helionetics on excimer and blue-green lasers for communications. In addition to the Ph.D., Dr. Sutton holds a B.M.E. in mechanical and administrative engineering from Cornell University. He also completed postdoctoral courses in supersonic aerodynamics, boundary layers, turbulence, plasma physics, and program management.

Carson W. Taylor, NAE, is retired from the Bonneville Power Administration (BPA), which he joined in 1969 after earning degrees from the University of Wisconsin and Rensselaer Polytechnic Institute. His interests include power system control and protection, system dynamic performance, ac/dc interactions, and power system operations and planning. He retired from BPA in January 2006 as a principal engineer in transmission operations and planning. He consults and has instructed and led many industry short courses. Mr. Taylor is a member of the National Academy of Engineering. He is a fellow of the IEEE and past chairman of the IEEE Power System Stability Controls Subcommittee. He is a convenor of three CIGRÉ task forces on power system voltage and angle stability. He is the author of the book *Power System Voltage Stability* (McGraw-Hill). The book is translated into Chinese. Mr. Taylor has authored or co-authored many IEEE and CIGRÉ papers.

Michael D. Williams is an associate professor in the Department of Physics and director of the Center of Excellence in Microelectronics and Photonics at Clark Atlanta University. He received his Ph.D. degree in physics from Stanford University in 1987. His research interest is the effects of growth morphology and interfacial strain on the electronic band structure and stoichiometry of epitaxially grown, compound semiconductors using surface-sensitive techniques such as UPS and SIMS. In particular, he has explored the mechanisms responsible for the segregation of indium in indium-based alloys and their subsequent effect on the performance of integrated optoelectronic device structures. He has exploited advances in microfabrication techniques to design and fabricate novel microelectronic and photonic device structures such as the negative electron affinity vacuum transistor and the freestanding quantum well. The latter structure consists of a quantum well confined on both sides by air or vacuum. It is ideal for probing the local properties of solids, e.g., the interaction of quantum confined states with surface or interface states. Dr. Williams is a former member of the technical staff in the Optoelectronics Research Department at AT&T Bell Laboratories, Holmdel, New Jersey. He joined AT&T in 1987 after completing an appointment as a visiting scientist at IBM's Almaden Research Center in San Jose, California. Dr. Williams joined the faculty of Clark Atlanta University in 1994. He has published more than 65 papers and has four patents. He is an active life member of the American Physical Society. He has chaired the APS Committee on Minorities, organized and chaired a special session for the Committee on Minorities, and served on the Nominating Committee for DMP. Dr. Williams is also a member of the AVS (formerly the American Vacuum Society) and the National Society of Black Physicists.

Appendix B

Committee Meetings

FIRST MEETING
JANUARY 24-25, 2007
HUNTSVILLE, ALABAMA

Meeting Objectives

Introduce committee members to the National Academies and the Board on Army Science and Technology; conduct composition and balance discussion; discuss statement of task and sponsor expectations; receive orientation presentations on the mission, organization, and functions of the U.S. Army Space and Missile Defense Command/Army Forces Strategic Command; receive presentations regarding emerging technologies relevant to the statement of task; consider and approve draft outline; and make writing assignments.

Presenters

Sponsor's Welcoming Remarks
Mark Swinson, *Chief Scientist, U.S. Army Space and Missile Defense Command/Army Forces Strategic Command*

Directed Energy Combat Development Overview
Daryl Youngman, *U.S. Army Air and Missile Defense Battle Laboratory*

Joint High Power Solid State Laser (J-HPSSL)
Adam Aberle, *U.S. Army Space and Missile Defense Command/Army Forces Strategic Command*

HEL-JTO Overview
Don Seeley, *Deputy Director, U.S. Army Space and Missile Defense Command/ Army Forces Strategic Command*

Briefing to National Academy of Sciences' Committee on Directed Energy Technology for Countering Indirect Weapons
Daniel Trainor, *Textron Corporation*

High Energy Laser Technology Demonstrator (HEL TD) Weapon System Program
Bill Gnacek, *U.S. Army Space and Missile Defense Command/Army Forces Strategic Command*

HELTD Lethality & Systems Assessment
Chuck Lamar, *U.S. Army Space and Missile Defense Command/Army Forces Strategic Command*

Introduction
Jackie Gish, *Northrop Grumman Corporation*

THEL, MTHEL & HEL Block 0
John Nugent, *Northrop Grumman*

3 – Laser Segment
Jay Marmo, *Northrop Grumman Corporation*

Thermal Management
Jackie Gish, *Northrop Grumman Corporation*

SSL Performance Projections
Jackie Gish, *Northrop Grumman Corporation*

Summary
Jackie Gish, *Northrop Grumman Corporation*

SECOND MEETING
FEBRUARY 26-27, 2007
WASHINGTON, D.C.

Meeting Objectives

Conduct final composition and balance discussion; continue receiving presentations regarding emerging technologies relevant to the statement of task; consider and approve the concept draft report; and make additional writing assignments.

Presenters

Directed Energy Systems
Patrick K. Garvey, *Boeing Missile Defense Systems*

Thin Disk Laser Technology Update to Board on Army Science & Technology
Edward W. Pogue, *Boeing Missile Defense Systems*

Counter RAM/Counter ManPADS/Counter Battery
Lee Gutheinz, *Boeing Missile Defense Systems*

Modeling & Simulation
Edward W. Pogue, *Boeing Missile Defense Systems*

Advanced Tactical Laser (ATL) Advanced Concept Technology Demonstration (ACTD)
Don Slater, *Boeing Missile Defense Systems*

Directed Energy Systems Power and Energy Systems
Gary Grider, *DRS-TEM, Inc.*

Laser Area Defense Near-Term Employment Concept
Jim Horkovich, *Raytheon Directed Energy Weapons*

C-RAM Lethality
Rusty Graves and Wendell Cook, *U.S. Army Space and Missile Defense Command/Army Forces Strategic Command*

Modeling and Simulation Support to HEL System Development
Wendell Cook, *BAE Systems*

Phalanx, Fiber Laser, and Option 1 JHPSSL
Frank Brueckner, *Raytheon Corporation*

The Army's Hybrid Electric Initiative
Gus Khalil, *U.S. Army Tank-Automotive Research, Development, and Engineering Center*

THIRD MEETING
APRIL 3-4, 2007
WASHINGTON, D.C.

Meeting Objectives

Conduct final composition and balance discussion; continue receiving presentations regarding emerging technologies relevant to the statement of task; consider and approve the first full message draft report; and make additional writing assignments.

Presenters

Long Term Use of a BCS
Brian Strickland, *U.S. Army Space and Missile Defense Command/Army Forces Strategic Command*

DPSSL Illuminator Technology Development (and scaling SSLs to higher power)
Stephen G. Post, *Missile Defense Agency*

Army Research Laboratory-Enabling Technologies for Directed Energy Solid State Diode Pumped Lasers
Gary Woods, *U.S. Army Research Laboratory*

Status of Onshore Produced Ceramic Laser Gain Materials
Rick Gentilman, *Raytheon Corporation*

Air Force Laser Programs
R. Andrew Motes, *U.S. Air Force Research Laboratory*

Extended Area Protection & Survivability (EAPS) System Sensor Suite Requirements, Radars for C-RAM
Jim Mullins, *Aviation and Missile Research, Development, and Engineering Center*

C-RAM and Force Encampment Protection System (FEPS) Programs
Pete Kirkland, *U.S. Army Space and Missile Defense Command/Army Forces Strategic Command*

Advanced Tactical Technology–High Energy Lasers
Stephen Welby, *Defense Advanced Research Projects Agency*

Lockheed Martin DE Overview
Kenneth W. Billman, *Lockheed Martin Corporation*

J-HPSSL Phase 3 (Option-1) Conceptual Design for ThinZag® Laser on an FCS-Like Ground Vehicle
Chas. W. von Rosenberg, Jr., *Textron Corporation*

FOURTH MEETING
MAY 7-8, 2007
IRVINE, CALIFORNIA

Meeting Objectives

Continue deliberations on the report; come to agreement on the findings and recommendations; prepare necessary written input; determine whether sensitive appendix is required; concur that the report is ready for peer review.

Presenters

None

Appendix C

Abbreviations and Acronyms

BAST	Board on Army Science and Technology
BQ	beam quality
COTS	commercial off the shelf
C-RAM	counterrocket, -artillery, and -mortar
DARPA	Defense Advanced Research Projects Agency
DE	directed energy
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
FY	fiscal year
HEL	high-energy laser
HELLADS	High Energy Liquid Laser Area Defense System
kW	kilowatt
LLNL	Lawrence Livermore National Laboratory
NGST	Northrop Grumman Space Technology
NRC	National Research Council
RAM	rockets, artillery, and mortars

SMDC/ ARSTRAT	U.S. Army Space and Missile Defense Command/Army Forces Strategic Command
SSL	solid-state laser
THEL	tactical high-energy laser
TRL	technology readiness level
U.S.C.	United States Code

Appendix D

Definitions of Technology Readiness Levels

TABLE D-1 Definitions of Technology Readiness Levels (TRLs)

TRL	Definition
Level 1	Basic principles observed and reported
Level 2	Technology concept and/or application formulated
Level 3	Analytical and experimental critical function and/or characteristic proof of concept
Level 4	Component and/or breadboard[a] validation in laboratory environment
Level 5	Component and/or breadboard validation in a relevant environment
Level 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
Level 7	System prototype demonstration in an operational (space) environment
Level 8	Actual system completed and (flight) qualified through test demonstration (ground and space)
Level 9	Actual system (flight) proven through successful mission operations

[a]Temporary prototype of an electronic circuit used for experimenting with circuit designs.