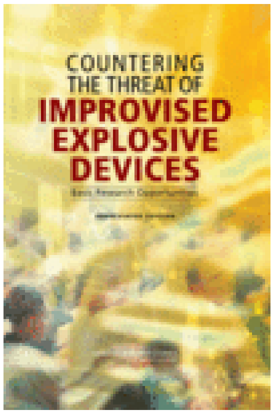

Countering the Threat of Improvised Explosive Devices: Basic Research Opportunities, Abbreviated Version

Committee on Defeating Improvised Explosive Devices: Basic Research to Interrupt the IED Delivery Chain, National Research Council

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COUNTERING THE THREAT OF IMPROVISED EXPLOSIVE DEVICES

Basic Research Opportunities

ABBREVIATED VERSION

Committee on Defeating Improvised Explosive Devices:
Basic Research to Interrupt the IED Delivery Chain

Board on Chemical Sciences and Technology
Division on Earth and Life Studies

Naval Studies Board
Division on Engineering and Physical Sciences

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Preface

Attacks in London, Madrid, Bali, Oklahoma City, and other places indicate that improvised explosive devices (IEDs) are among the weapons of choice of terrorists throughout the world. IEDs have emerged as the primary method of asymmetric warfare[1] for terrorists and insurgents in Iraq and elsewhere. US counter-IED efforts to date have used mainly off-the-shelf technologies; as these technologies have been deployed, terrorists and insurgents have adapted their tactics to counter the countermeasures. With their own access to a wide array of commercially available technologies, insurgents have shown a cycle of adaptation that is short relative to the ability of US forces to develop and field IED countermeasures.

Scientists and engineers have developed various types of counter-IED technologies, such as explosive-detection sensors, electronic jamming devices, and surveillance systems. Those devices have been used with some success to counter individual IED attacks, but events in Iraq indicate that the effectiveness of IEDs as weapons of asymmetric warfare remains.

In February 2006, the Deputy Secretary of Defense signed Department of Defense (DoD) Directive 2000.19E, Joint Improvised Explosive Device Defeat Organization (JIEDDO), changing the name of the Joint IED Defeat Task Force (formed on June 27, 2005) and establishing JIEDDO as a joint

[1]Asymmetric warfare is "leveraging inferior tactical or operational strength against the vulnerabilities of a superior opponent to achieve disproportionate effect with the aim of undermining the opponent's will in order to achieve the asymmetric actor's strategic objectives" (McKenzie, 2001).

entity and jointly manned activity.[2] JIEDDO's mission is to "focus (lead, advocate, coordinate) all DoD actions in support of combatant commanders and their respective joint task force efforts to defeat IEDs as weapons of strategic influence." The Office of Naval Research (ONR), as part of the overall DoD effort, is investing in middle- and long-term basic research to expand the array of options available for countering the use of IEDs.[3] This effort extends beyond identifying and negating the devices themselves or their components to addressing all actions preceding and following the emplacement and detonation of the devices.

TERMS OF REFERENCE

At the request of ONR, the National Academies agreed to the following:

> The National Academies will examine the current state of knowledge and practice in the prevention, detection, and mitigation of the effects of improvised explosive devices (IEDs) and make recommendations for avenues of basic research toward the eventual goal of making these devices an obsolete method of asymmetric warfare. The review will consider the following steps in countering IEDs:
>
> - Prediction and prevention of the assembly and use of IEDs;
> - Detection of the IED or its components; and
> - Controlled detonation of the IED prior to the intended attack.
>
> The review will ascertain the basic research questions in physical science, social science, and engineering that, if answered, could lead to new methods of countering use of IEDs, and engage an interdisciplinary cross-section of the relevant research communities in suggesting specific avenues of research that could prove promising in the pursuit of those answers.

THE COMMITTEE'S APPROACH

The Committee on Defeating Improvised Explosive Devices: Basic Research to Interrupt the IED Delivery Chain[4] was challenged to deliver useful information to ONR on a broad, extremely multidisciplinary topic in a period (1 year) that was relatively short given the complexity of

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[2]February 14, 2006. DoD Directive 2000.19E.

[3]At the outset of this study, the Technical Director and Chief Scientist of ONR was appointed to serve as chair of the JIEDD Laboratory Board (JLB), which was established to coordinate, synchronize, and sponsor middle- and long-term research, development, science, and technology that contribute to countering the IED threat. The status of the JLB structure was unclear at the time this report was completed.

[4]Brief biographies of all committee members are presented in Appendix A.

the problem. To achieve that objective, the committee organized itself around specific technical subjects. The discussions in and structure of the committee's report reflect that organization. The subjects were deemed of high priority either because of their applicability to the problem of IEDs and the relative lack of investment in these areas or because of promising research opportunities that the information provided to the committee and the committee members' own experience indicated were untapped.

The committee first convened in November 2005 and held meetings over a period of 7 months to gather input from relevant communities and to deliberate on its findings and recommendations. A summary of the committee's data-gathering meetings is provided in Appendix B. The months after the committee's meetings were spent in preparing the draft manuscript, gathering additional information, reviewing and responding to external-review comments, editing the report, and conducting the security review to produce this version of the report that does not disclose information as described in 5 U.S.C. 552(b).

Many of the research subjects discussed here are worthy of much more detailed treatment than is possible in a report of such broad scope. Accordingly, the committee will be subsequently involved in organizing and executing two workshops, which will allow ONR to explore the more challenging research areas in additional depth with a larger cross-section of the research community. That will serve the dual purposes of helping ONR to frame its research programs and providing a forum to facilitate interactions between ONR and researchers in areas in which ONR has not traditionally been active. A brief summary resulting from the workshops will be issued.

During the course of its study, the committee identified research avenues for countering IEDs that were clearly basic and others that might be considered basic by some but applied by others. Given the urgency and criticality of the IED threat, the committee felt that all its research recommendations should be discussed in this report, especially in light of the roles and responsibilities of ONR with respect to coordinating, synchronizing, and sponsoring both middle- and long-term research, development, science, and technology that could contribute to countering the IED threat. The committee anticipates that not only ONR but other entities, including those in JIEDDO, will read this report and have an opportunity to act on its suggestions—providing reason to be inclusive rather than exclusive when considering whether a research recommendation fell within the bounds of "basic" research.

The sensitive nature of much of the information concerning IEDs and their use presented a challenge in the writing of the committee's report. The committee's report has been determined to contain information exempt from mandatory disclosure under 5 U.S.C. 552(b).

Section 15 of the Federal Advisory Committee Act provides that the National Academies shall make its final report available to the public unless the National Academies determines that the report would disclose matters described in one or more of the exemption provisions under the Freedom of Information Act (FOIA). If the National Academies determines that the report will disclose matters described in one or more of the FOIA exemptions, the National Academies "shall make public an abbreviated version of the report that does not disclose those matters." This unrestricted, abbreviated version of the committee's report was written to fulfill the National Academies' statutory obligation. This abbreviated version fully represents, insofar as possible, the committee's conclusions, recommendations, and other substantive material without disclosing matters described in title 5 U.S.C. section 552(b).

Copies of the committee's full report are available to the government and Department of Defense contractors by contacting the National Research Council's Board on Chemical Studies and Technology (http://dels.nas.edu/bcst/index.shtml). Other requests will be considered on a case-by-case basis.

Acknowledgment of Reviewers

National Research Council (NRC) reports are reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making the published reports as sound as possible and to ensure that the reports meet institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. Although the reviewers provide many constructive comments and suggestions, they are not asked to endorse the conclusions or recommendations, nor do they see the final draft of reports before release.

We thank the following for their review of the draft report:

Mr. Thomas K. Burris, Lockheed Martin Corporation, Fort Worth, TX
Dr. Anthony A. Cantu, U.S. Secret Service, Springfield, VA
Mr. Michael Eisenstadt, The Washington Institute for Near East Policy, Washington, DC
Dr. Carl W. Lineberger, University of Colorado, Boulder
MajGen Thomas S. Jones, United States Marine Corp, Retired
Mr. Gary LaFree, University of Maryland, College Park
Dr. Butler W. Lampson, Microsoft Corporation, Cambridge, MA
Dr. Donald Prosnitz, Lawrence Livermore National Laboratory, Livermore, CA

Mr. Michael Sheehan, New York University, New York
Dr. Richart E. Slusher, Lucent Technologies, Murray Hill, NJ

The review of the draft report was overseen by R. Stephen Berry, University of Chicago, and Hyla S. Napadensky, Napadensky Energetics Inc. (retired). Appointed by the NRC, they were responsible for making certain that an independent examination of the draft report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of NRC reports rests entirely with the authoring committee and the institution.

Contents

Summary

Improvised explosive device (IED) is defined here as an explosive device that is placed or fabricated in an improvised manner; incorporates destructive, lethal, noxious, pyrotechnic, or incendiary chemicals; and is designed to destroy, incapacitate, harass, or distract. IEDs may incorporate military stores, but they are normally devised from nonmilitary components. They are as varied as "command-detonated" pipe bombs, "booby-trapped" military ordnance, and car bombs. They always contain explosive materials, detonators, and triggering mechanisms; they are often cased and may use shrapnel. The term *improvised* may apply either to the construction of the device or to its use by irregular forces. Thus, a mine produced for regular forces may be considered an IED if it is used by irregular forces, but an unmodified mine placed by regular forces is not considered an IED. Explosive devices designed to disperse chemical, biological, or radiological material are generally not classified as IEDs and were not considered for this study.

THE IED THREAT

Throughout history, and with varying effectiveness, groups have resorted to the use of IEDs to advance a particular cause or wear down an adversary. IEDs are used by terrorists to strike soft targets and by insurgents as weapons against a stronger enemy. They can be made at relatively low cost, are relatively easy to construct and emplace, and can achieve both strategic and tactical results.

The concerted use of IEDs to achieve an adversary's strategic or tactical goals is referred to as an IED campaign. Two fundamental aspects of an IED campaign are its asymmetry and idiosyncratic nature.[1] Overarching the IED campaign is the sociopolitical context of the insurgency or terrorist group that carries it out. The adversary's objective, beyond casualties, is usually to affect the psychology of the local population or the populations of other engaged nations by creating fear, instability, or discomfort. The adversary expects to move these audiences in ways advantageous to their cause. Counter-IED and counterinsurgency efforts are inexorably linked, and counterinsurgency concepts can be used as tools to defeat an IED campaign.

The ability of the adversary to learn and adapt has been an important characteristic of IED campaigns. The time needed to adapt has typically been shorter than the time needed by counter-IED forces to deploy and implement IED countermeasures. Moreover, IED countermeasures often have the effect of shifting the threat from one device or tactic to another.

In an IED campaign, the adversary must carry out numerous steps before initiating an IED attack. That process includes obtaining funding and bomb materials, recruiting people, constructing the device, selecting the target, delivering the device to its target, carrying out the attack, and disseminating information about the attack for propaganda or other purposes. Together, such steps make up the IED threat chain.

The elements of the threat chain can be grouped into three basic components: organization, resources, and operations. The adversary must have an organization of trusted people with secure communication, connections to outside sources of support, a public interface for recruitment and publicity, and some degree of popular support or tolerance. Destabilization of the organization would inhibit the ability to field an effective IED campaign. Key resources needed to support an IED campaign include people, materiel, money, information, facilities, and access to social networks. For each of those essential resources, there are observables, signatures, and opportunities for interception, tagging, tracking, rigging, or otherwise exploiting the contact to gain access to, or information about, the organization. Operations include items directly associated with the IED device, from weapon manufacture, storage, preparation activities, and the attack itself through postattack evasion. Most of the Department of Defense IED-defeat effort has been devoted to operations, which most resemble traditional military operations.

[1] Asymmetry is the absence of a common basis of comparison with respect to a quality or a capability; idiosyncrasy is possession of a peculiar or eccentric pattern.

COUNTERING THE IED THREAT

An ideal approach to defeating the IED threat would include a set of integrated efforts aimed at squeezing the adversary at each stage of the IED threat chain. However, limitations in understanding or in technical capabilities prevent that. The limitations suggest areas of basic research that are relevant to the IED challenge, and those areas are set out below.

Relationships Between the Human Terrain and the IED Threat

The human terrain—the political, social, cultural, and economic environment—is a critical element at all stages of an IED attack, and it probably is also the most complex and the least well understood. Within the social and behavioral sciences, numerous methods can be used in novel counter-IED research. Formal mathematical modeling, statistical or quantitative analysis, and qualitative work, such as case studies and focused historical comparisons, can play an important role. Comparative case studies based on field research could be useful where such work is feasible. Survey research is highly relevant. Red teaming, gaming, and simulations may be useful to enhance prediction. A social-sciences research program aimed at countering IEDs would integrate a variety of behavioral and social-science methods and link social-science knowledge to the methods proposed by science and technology.

Data Acquisition, Data Fusion, and Analysis

There is a need to detect the activities that precede IED use so as to predict events well before an IED detonation. That requires a wide variety of information including data from both human and technical sources, and the systematic inference of actionable knowledge from the fusion of the data. US forces need the capability to extract strategic and tactical actionable intelligence information from massive amounts of diverse, potentially incomplete, and noisy data in a timely and dynamic fashion.

Analytical Techniques for Assessing IED Countermeasures

Analytical methods that quantitatively assess the effectiveness of IED countermeasures are needed. There are some studies about the evaluation of counter-suicide-bombing measures in Israel, and the effectiveness of airline-passenger screening, but to the committee's knowledge there is nothing in the scientific literature regarding the evaluation of IED countermeasures.

Detection and Disruption Throughout the IED Threat Chain

There are various points in the chain of events leading up to an IED attack at which improved detection and disruption technologies might be usefully applied. For each detection opportunity, there are basic-research issues regarding the particular signatures, methods, and limits of detection. With respect to disruption, technical opportunities exist to improve current approaches or to make them more readily fielded in theater.

Resource Availability and the IED Threat

Available resources—energetic material, initiators, triggering devices, knowledge, finances, and facilities—are critical in determining the type, number, and effectiveness of IED attacks and directly influence the potential for detection and countermeasures. New capabilities and associated basic research are needed to exploit the dependence of the IED threat on those resources.

RESEARCH RECOMMENDATIONS

A major portion of the current IED activities presented to the committee appears to be focused on the operational aspects of the IED threat, the aspects most readily addressed by conventional military means. The recommendations reported here are intended to supplement ongoing work and to provide a broader focus on disrupting the entire IED threat chain. The following recommendations represent research challenges in the five areas discussed above that are compelling based on their potential impact, the potential timeline for their payoff, and the relative level of current effort in these areas.

- **Identify the most important and most vulnerable elements in the IED threat chain.**

Research should include identifying and analyzing key elements of the threat chain, such as recruitment, availability of technical expertise, diffusion of knowledge, popular support, and the networks and relationships among players. Research should develop a general understanding of how decisions (especially those related to innovations, methods, targets, and timing) are made and how information is communicated in underground organizations, and should examine adversary attitudes toward risk. Due to the role public support, tolerance, or aversion can play in an IED campaign, research should seek to develop better ways of gauging public opinion in different cultural, social, and political contexts and should develop a better understanding of the role of emotion, interpretation, understanding, values, images, and symbols in the IED threat and investigate potential mechanisms for delegitimizing and devaluing IEDS. Such research should draw on the fields of political science, political economy, sociology, religion, psychology, media and communication, criminology, terrorism studies, anthropology, history, operations research, and international studies. Decision theory, risk, cultural anthropology, and appropriate regional expertise are particularly relevant.

- **Use lessons learned from other conflicts and contexts (e.g., law enforcement) to develop concepts, propositions, and models that can be applied more generally.**

Analysis of the IED problem should not focus exclusively on current conflicts but should anticipate other potential conflict zones by using the social sciences. Systematic attention should be paid to lessons learned and to their future application. Research can elucidate where and when the threat may migrate and what form it is likely to take. Research subjects include how ideas and tactics are imitated and migrate within and between cultures and societies, the relationship between local insurgents or political factions and transnational terrorist conspiracies, and the role of the media, including the Internet, as a communications tool for terrorists/insurgents. The role of the Internet as a source of information for constructing IEDs and for promoting the cross-national diffusion of ideas and tactics is a particularly important issue that should be examined. Researchers in political science, sociology, psychology, criminology, anthropology, history, media and communication, and international studies can all make valuable contributions.

- **Develop a deeper understanding of sectarian, ethnic, clan, and tribal divisions in societies.**

Research should address the continued development of theory and data to map patterns of social networks, especially during times of conflict and stress. Social-network research can be engaged to understand the conditions and characteristics that could encourage the formation of new networks that support security and stabilization rather than disruption and violence. Research can explore how identities are formed in and sustained by networks, how ethnicity or religion becomes a determinant of identity and may become a catalyst of violence, and how ethnic and sectarian divisions can be overcome. Research should aim to understand the dynamics of societies in the face of rapid and fundamental change. Studies should examine how to undermine terrorism or move to democracy for societies that have a variety of cleavages, values, and cultures. Researchers need to develop a deep understanding of varied cultures and societies and not focus only on those prone to violence; regionally focused research may be appropriate. The disciplines of cultural anthropology, religion, sociology, history, political science, criminology, and international studies can contribute.

- **Develop designs and approaches for inference frameworks that can accommodate massive, diverse, incomplete, and/or noisy data sources.**

Automated data-collection produces massive amounts of data that may be incomplete and noisy. The timely, accurate use of the data will require the ability to automate data integration and analysis. Research should answer:

- How to model intelligence information development and decision making.
- How to produce reliable, actionable information from noisy, temporal, and partial data.
- How to develop the means to intelligently process data and information.

Research should include development of methods to integrate data from diverse sources into a single inference structure; of open-architecture inference engines that can support new plug-in sensor packages and data sources; and of prototypes for massively scalable data storage and processing architectures. Computer and computational scientists and researchers in data acquisition and analysis, data representation and statistical inference, image interpretation, and sensors can make valuable contributions.

- **Develop conceptual bases for identifying both known and potential classes of IED threat events.**

The ability to identify different types of IED threats in different contexts requires understanding the signatures associated with the threats and the types of data and intelligence information needed to detect those signatures. Such an understanding would provide a basis for developing data collection requirements. This understanding is needed for known classes of IED threats and potential new classes. Research should include developing models of the relationships between threat events and actionable information and defining the requirements for sensor types and ancillary data. Specifying those relationships and requirements will further the development of sensors to acquire the data needed to generate actionable information for a given set of threat events. Computational and behavioral (social, cultural, and geopolitical) scientists and the military, law-enforcement, and intelligence communities should be involved in this research.

- **Understand existing approaches to evaluating IED countermeasures, and establish new metrics and analytical methods for analyzing, assessing, and modeling the operational effectiveness of IED countermeasures quantitatively and qualitatively, recognizing that insurgents/terrorists will change their behavior in response to countermeasures.**

Metrics and analytical methods for assessing IED countermeasures would allow identification of what works, what does not work, and why. Specifically, research should seek to determine trends in overall counter-IED operational effectiveness; determine the relative effectiveness of different counter-IED systems and tactics; discern differences and trends in adversary systems and tactics in different areas; design, test, and evaluate new systems, tactics, and operational concepts; anticipate and pre-empt adversary countermeasures against new systems and tactics; and provide realistic and dynamic simulations. Improved analytical tools would support program planning, operational planning, tactical development, and counter-IED training. Research in statistics, game theory, operations research, military research, and social, cognitive, and economic sciences can make valuable contributions.

- **Enhance capabilities for persistent surveillance.**

Improvements in persistent surveillance can provide capabilities throughout the IED threat chain. The key research questions can be divided among platform development, sensor development, and image- and data-processing. Another area for study is the control, coordination, and communication of a large number of assets. Persistent surveillance has the potential of generating vast quantities of data. To be useful, improved data storage and transmission, mining, analysis, and processing methods must be developed. There is substantial research in those areas in various agencies, but additional targeted efforts funded by the Department of Defense are encouraged. Researchers in the following fields can contribute: solid-state device research; networking and communication engineering; computer science; mechanical, control, and aeronautical engineering; electrical and optical engineering; and probabilistic inference (for example, computationally limited inference algorithms).

- **Determine the fundamental physical limits on the active and passive detection of arming and firing systems, as well as the physical and chemical limitations for trace and standoff detection.**

The desire to meet the challenges of detection must be grounded in the fundamental physical and chemical limits of detection and take into account reasonable extrapolations of existing technology. Quantifying and understanding the variability of background concentrations will help determine the theoretical performance limit of detection systems. Similarly, the physical limits of detecting the electromagnetic signatures of arming and firing systems must be determined in the context of background interferences. Research will be needed in chemical, environmental, and electrical engineering; chemistry and analytical chemistry; applied physics; forensic science; spectroscopy; and optics.

- **Develop new methods of remote and standoff detection, and continue the development and improvement of sampling-based methods for the detection of explosives in the field.**

Reliable and rapid explosive detection in a field environment is an unsolved problem. Substantial research and development efforts are under way, but further advances are needed. They may require research in plume and aerosol dynamics; x-ray, microwave, infrared, and terahertz imaging and spectroscopy; neutron, gamma-ray, magnetic resonance, and magnetic-field systems; optical absorption and fluorescence; light detection and ranging (LIDAR), differential-absorption LIDAR (DIAL), and differential-reflectance LIDAR (DIRL); biosensors and biomimetic sensors; and microelectromechanical systems (MEMS). Researchers in chemical, mechanical, nuclear, and electrical engineering, bioengineering, chemistry, spectroscopy, applied physics, and optics should be involved in these efforts.

- **Perform case studies of actual IED construction and events to determine whether and how resource control might be implemented, with the eventual goal of developing the ability to model the connection between resources and the IED threat chain.**

The availability of resources helps to determine the type, number, and effectiveness of IED construction; the ease or danger of manufacture and deployment; the lethality achieved; and the potential for detection and countermeasures. Key questions to be answered using case studies include these:

- What energetic materials, initiators, triggering devices, and other materials were used, how were they obtained, and how was the IED delivered?
- Why were some tactics, materials, and devices used in particular conflicts and contexts but not others?
- What explosive precursor materials are or might become threats,

and what methods can be used to diminish the threats (such as tracking, control, substitution, and adulteration)?

- How does the availability of explosive precursors vary geographically?

Process and chemical engineers, explosives chemists, researchers who study historical and current terrorism, researchers in international studies, and operations researchers can make valuable contributions to answering those questions. The integration of that research in a way that recognizes the interplay of resources, human behavior, and context will be invaluable. Interactions between the researchers and customs officials, persons with expertise in tracking and resource management, and persons in manufacturing and professional organizations are recommended.

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Appendix A

Committee Membership

John L. Anderson (Chair), (NAE) is provost, university vice president, and a professor of chemical engineering at Case Western Reserve University. He served on the faculty of Cornell University for 5 years before joining the faculty at Carnegie Mellon University in 1976, where he served until 2004. Dr. Anderson is a member of the National Academy of Engineering (NAE) and has chaired the NAE chemical engineering section. He is a fellow of the American Academy of Arts and Sciences, the American Association for the Advancement of Science, and the American Institute of Medical and Biological Engineering. He is the author of more than 100 journal articles and book chapters. He received his bachelor's degree from the University of Delaware and his PhD in chemical engineering from the University of Illinois.

Alan Berman is an independent consultant whose current clients include the Applied Research Laboratory of Pennsylvania State University and the Center for Naval Analyses. Dr. Berman's expertise includes Navy research and development investments, space operations capabilities, information operations, and command, control, communications, computers, intelligence, surveillance, and reconnaissance programs. Dr. Berman served as dean of the Rosenstiel School of Marine and Atmospheric Sciences at the University of Miami, where he was responsible for the graduate programs in physical oceanography, marine biology, geology, geophysics, applied ocean science, and underwater acoustics; and as director of research at the Naval Research Laboratory, where he administered broad programs in basic and applied research.

Charles A. Bouman is professor of electrical and computer engineering and biomedical engineering at Purdue University. His research focuses on the use of statistical image models, multiscale techniques, and fast algorithms in applications that include medical and electronic imaging. Dr. Bouman received his PhD in electrical engineering from Princeton University and his MS degree from the University of California, Berkeley. He is a fellow of the Institute of Electrical and Electronics Engineers, a fellow of the American Institute for Medical and Biological Engineering, and of the Society for Imaging Science and Technology.

William F. Brinkman (NAS) is a senior research physicist in the Physics Department at Princeton University. He retired as vice president for research from Bell Laboratories, Lucent Technologies, on September 30, 2001. In that position, his responsibilities included the direction of all research to enable the advancement of the technology underlying Lucent Technologies's products. He is a member of the National Academy of Sciences (NAS), the American Philosophical Society, and the American Academy of Arts and Sciences. He has served on a number of national committees, including chairmanship of the NAS Physics Survey and the National Research Council Committee on Solid-State Sciences. He is past president of the American Physical Society and is currently chairman of the National Laboratories Operations Board of the Department of Energy. Dr. Brinkman was the recipient of the 1994 George E. Pake Prize.

Martha Crenshaw is the Colin and Nancy Campbell Professor of Global Issues and Democratic Thought and professor of government at Wesleyan University, in Middletown, Connecticut, where she has taught since 1974. She has written extensively on political terrorism. Her recent work includes the chapters "Coercive Diplomacy and the Response to Terrorism" in *The United States and Coercive Diplomacy*, published by the Institute of Peace, and "Terrorism, Strategies, and Grand Strategies" in *Attacking Terrorism* published by Georgetown University Press. She serves on the Executive Board of Women in International Security and chairs the American Political Science Association Task Force on Political Violence and Terrorism. The International Society of Political Psychology, of which she is a past president, awarded her its Neville Sanford award for Professional Contributions to Political Psychology in 2004. She received her PhD from the University of Virginia in 1973. Her BA is from Newcomb College of Tulane University.

Mary Lou Fultz is associate director of the US Postal Service Crime Laboratory. Dr. Fultz was chief of the Forensic Science Laboratory for the Bureau of Alcohol, Tobacco and Firearms. She received her PhD in chemistry from the University of Maryland.

William J. Hurley has been with the Institute for Defense Analyses (IDA) since 1985 and is currently assistant director of the System Evaluation Division. From 1975 to 1985, Dr. Hurley was with the Center for Naval Analyses. Dr. Hurley's research has addressed a variety of defense issues with emphases in joint forces, analytical methods, advanced technologies, naval forces, and undersea warfare. He has directed or been coauthor of over 30 studies sponsored principally by the Office of the Secretary of Defense and the Navy. In 1993, Dr. Hurley received IDA's Andrew J. Goodpaster Award for Excellence in Research. In addition to his research responsibilities, Dr. Hurley was the associate program director and then program director of the Defense Science Study Group (DSSG) from 1991 to 1998. The DSSG is a program of education and study that introduces outstanding young professors of science and engineering to military systems and organizations and current issues of national security. The program is sponsored by the Defense Advanced Research Projects Agency. Dr. Hurley's academic background is in mathematical physics. He received a BS in physics from Boston College (1965) and a PhD in physics from the University of Rochester (1971), and he held research positions at Syracuse University (1970-1972) and at the University of Texas (1972-1975).

Anil K. Jain is a University Distinguished Professor in the Department of Computer Science and Engineering at Michigan State University. He received his BTech from the Indian Institute of Technology Kanpur and his MS and PhD from Ohio State University. His research interests include statistical pattern recognition, computer vision, and biometric authentication. He received awards for best papers in 1987 and 1991 from the Pattern Recognition Society. He also received the 1996 *IEEE Transactions on Neural Networks* Best Paper Award. He is a fellow of the Institute of Electrical and Electronics Engineers, the Association for Computing Machinery, the American Association for the Advancement of Science, and the International Association for Pattern Recognition. He has received Fulbright, Guggenheim, and Humboldt awards. Holder of six patents in fingerprint-matching, he is the author of a number of books, including *Handbook of Face Recognition* and *Handbook of Fingerprint Recognition*. He is a member of the National Research Council study team on Whither Biometrics.

Harry W. Jenkins, USMC (Ret.), is an independent consultant and was the director of business development and congressional liaison at ITT

Industries-Defense, where he was responsible for activities in support of tactical communication systems and airborne electronic warfare between the Navy, Marine Corps, Coast Guard, National Guard, and appropriate committees in Congress. Major General Jenkins's operational background is in expeditionary warfare, particularly in regard to its mission use of command, control, communication, computers, and intelligence (C4I) systems. During Desert Storm, Major General Jenkins served as the commanding general of the Fourth Marine Expeditionary Brigade and directed operational planning, training and employment of the ground units, aviation assets, and command and control systems in the 17,000-member amphibious force. His last position before retirement from the US Marine Corps was director of expeditionary warfare for the chief of naval operations. In that position, he initiated a detailed program for C4I systems improvements for large-deck amphibious ships, managed all programs of naval mine warfare, and reorganized the Navy's unmanned aerial vehicle efforts for operations from aircraft carriers and amphibious ships. He is a member of numerous professional societies, including the Marine Corps Association, the Marine Corps Aviation Association, the Expeditionary Warfare Division of the Naval Defense Industry Association, the Navy League, and the Adjutants General Association of the United States. Major General Jenkins is a member of the Naval Studies Board.

Edward H. Kaplan (NAE/IOM) is the William N. and Marie A. Beach Professor of Management Sciences, professor of public health, and professor of engineering at Yale University. He received his bachelor's degree from McGill University and proceeded to graduate study at the Massachusetts Institute of Technology, where he completed three master's degrees (in operations research, city planning, and mathematics) in addition to his doctorate in urban studies. Dr. Kaplan is an expert in operations research, mathematical modeling, and statistics and has recently developed novel methods for quantitatively evaluating operational effectiveness of suicide-bomber-detector schemes. Dr. Kaplan is a member of the Institute of Medicine and the National Academy of Engineering.

Alexander MacLachlan (NAE), recently a member of the National Research Council's Board on Radioactive Waste Management, is coauthor of *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*. Before his retirement in March 1996, Dr. MacLachlan was deputy under secretary for R&D management at the US Department of Energy and held various other positions in the department. Earlier, he was employed by E. I. du Pont de Nemours and Company for 36 years, where he was senior vice president for research and development and chief technical officer from 1986 to 1993 and a member of DuPont's operating group from 1990 to 1993. He is currently president of the University of Delaware Research Foundation. Dr. MacLachlan received a B.S. in chemistry from Tufts University (1954) and a PhD in physical organic chemistry from the Massachusetts Institute of Technology (1957). He is a member of Phi Beta Kappa and was elected to the National Academy of Engineering in 1992.

Andrew W. Moore directs Google's Pittsburgh research facility and is a professor of robotics and computer science at the School of Computer Science, Carnegie Mellon University. His main research interest is data-mining—developing algorithms for finding all the potentially useful and statistically meaningful patterns in massive sources of data. His research strives to find real-world applications through the understanding of fundamental data structures, algorithms, and mathematics. Dr. Moore received his PhD in computer science and his undergraduate degree in mathematics from Cambridge University. After a postdoctoral fellowship at the Massachusetts Institute of Technology, he accepted his current position at Carnegie Mellon University.

Jimmie C. Oxley is professor of chemistry at the University of Rhode Island and codirector of the Forensic Science Partnership. After receiving her PhD from the University of British Columbia, Dr. Oxley joined the faculty of the New Mexico Institute of Mining and Technology, where she founded a PhD program in explosives and created the thermal-hazards research group. Dr. Oxley's laboratory specializes in the study of energetic materials. Most of the studies examine how and how fast these materials decompose. The goal is to understand their stability so that they may be handled safely. She received her BS from University of California, San Diego (1971); MS from California State University, Northridge; and her PhD from the University of British Columbia (1983).

Amy Sands is provost and academic vice president of the Monterey Institute of International Studies. Dr. Sands formerly served as deputy director of the Center for Nonproliferation Studies. From August 1994 to June 1996, she was assistant director of the Intelligence, Verification, and Information Management Bureau at the US Arms Control and Disarmament Agency (ACDA). Reporting to the ACDA director, she was responsible for managing the development of verification and compliance policy for relevant arms-control and nonproliferation activities, for ACDA's computer support and analysis activities, and for liaison with the intelligence community. Dr. Sands has taught courses at Boston College on political development, terrorism, and low-level violence and worked as the country risk manager at the Bank of New England. Dr. Sands holds a BA in political science from the University of Wisconsin and earned her MA, MALD, and PhD from the Fletcher School of Law and Diplomacy.

Joseph E. Shepherd is a professor of aeronautics at the California Institute of Technology (CIT) in Pasadena. He teaches and conducts research on fluid mechanics, chemistry, thermodynamics, structural mechanics of explosions, and related applications, such as propulsion. Dr. Shepherd has been a consultant and investigator on projects for the US Department of Energy, the US Nuclear Regulatory Commission, NASA, various national laboratories, the National Transportation Safety Board, and the aerospace and chemical industries. He started his career in explosions with his doctoral studies at CIT, where he received his degree in 1980 on "Dynamics of Vapor Explosions."

William C. Trogler is professor of chemistry at the University of California, San Diego. His current research focuses on inorganic chemistry applied to problems of environmental and technological interest. Dr. Trogler's research group is exploring the use of photoluminescent and electroluminescent silole polymers as sensors for detecting electron-deficient organics and explosives, the design of sensors specific for the fluorophosphonate G nerve agents, micellar catalysts incorporated into a porous silicon sensor to detect Sarin, and chemoresponsive transistors as manufacturable chemical sensors. He received his BA and MA from Johns Hopkins University in 1974 and his PhD from the California Institute of Technology in 1977.

Jonathan Young is head of the Safety and Risk Analysis Group of the Environmental Technology Division at Pacific Northwest National Laboratory. He has over 40 years of experience in systems and safety engineering, safety analysis, probabilistic safety assessment, and system-security activities in the aerospace and nuclear industries. He is principal instructor and course developer for numerous probabilistic safety-assessment courses, both in the United States and abroad. Mr. Young received his BA in mathematics from Lincoln University.

Appendix B

Summary of Data-Gathering Meetings

The Committee on Defeating Improvised Explosive Devices: Basic Research to Interrupt the IED Delivery Chain held three data-gathering meetings between November 2005 and April 2006. During these meetings, the committee received briefings from government officials, academics, and outside experts on the IED threat, IED countermeasures, terrorism, and insurgency.

November 7-8, 2005, in Washington, D.C. Briefings received from the following. Office of Naval Research (ONR): briefings on current ONR investments and counter-IED research efforts and purpose of the study and charge to the committee; Combating Terrorism Technology Task Force: IED threat and challenges facing the Department of Defense; Joint IED Defeat Task Force[1]: briefing on the role of the JIEDDTF and joint concept of operations. Briefings from the following university affiliated research centers on basic research efforts to counter IEDs: Applied Research Laboratories of the University of Texas, Applied Research Laboratory of the University of Washington, Applied Physics Laboratory of the Johns Hopkins University, and Applied Research Laboratory at the Pennsylvania State University. Lawrence Livermore, Los Alamos, and Sandia National Laboratories: briefings on counter-IED research ongoing at the Department of Energy's National Laboratories; Technology Support Working

[1]The Joint IED Defeat Task Force is now known as the Joint IED Defeat Organization (JIEDDO).

Group: briefing on the IED threat and currently deployed counter-IED technologies.

February 8-9, 2006, in Washington, D.C. Briefings received from the following. Office of Naval Research: briefing on ONR sponsored counter-IED research and ONR coordination with the JIEDDO and the Joint Laboratory Board; Office of the Secretary of Defense, Combating Terrorism Technology Task Force (CTTTF): briefing on the IED threat and insurgency; The Naval Postgraduate School: lessons from a graduate IED course; Washington Institute for Near East Policy, Military and Security Studies Program: briefing on the use of IEDs in Iraq and the Middle East; Institute for Defense Analyses, Joint Advanced Warfighting Program: briefing on the IED threat in Iraq; Breakout sessions with representatives from various federal agencies were held to receive briefings and participate in roundtable discussions on government counter-IED programs.[2]

April 18-19, 2006, in Washington, D.C. Briefings received from the following. Office of Naval Research: briefing on ONR sponsored counter-IED research; Office of the Director of Defense Research and Engineering: briefing on the Department of Defense counter-IED investment portfolio; Army Research Laboratory, Air Force Research Laboratory, Naval Research Laboratory: briefings on counter-IED research ongoing at the DoD service laboratories; Case Western Reserve University, Institute for Global Security Law and Policy: presentation on the legal aspects of countering IEDs; Core Operations Analysis Group (COAG): briefing on COAG support to the Joint IED Defeat Organization; Joint IED Defeat Organization: briefing on the IED threat, campaign, and future requirements; Breakout sessions with representatives from the RAND corporation, ONR, the Penn State University Applied Research Laboratory, the Massachusetts Institute of Technology Lincoln Laboratory, the DoD Joint Robotics Program Office, the Naval Research Laboratory and an independent consultant were held to discuss counter-IED research programs.

[2]Agencies represented included the Defense Intelligence Agency, Federal Bureau of Investigation, Secret Service, Department of State, Department of Homeland Security, Department of Energy, Department of Defense, Joint Chiefs of Staff and an intelligence agency.

Appendix C

Glossary

Asymmetry: the absence of a common basis of comparison with respect to a quality or a capability.

Data fusion: a formal framework in which means and tools for the alliance of data from different sources are expressed. It aims at obtaining information of greater quality; the exact definition of *greater quality* will depend upon the application (Wald, 1999).

Disruption: an action that interrupts, disables, or prematurely activates the detonation sequence of an IED.

Human terrain: the political, social, cultural and economic environment.

IED campaign: the concerted use of IEDs to achieve strategic or tactical goals.

Insurgency: A struggle between a non-ruling group and the ruling authorities in which the non-ruling group consciously uses political resources (such as organizational expertise, propaganda, and demonstrations) and violence to destroy, reformulate, or sustain the basis of legitimacy of one or more aspects of politics (O'Neil, 1990). Terrorism may be a tactic used in an insurgency.

JIEDDTF: Joint IED Defeat Task Force

JIEDDO: Joint IED Defeat Organization

ONR: Office of Naval Research

Ordnance: munitions, weapon-delivery system, or item that contains explosives, propellants, or chemical agents.

Persistent surveillance: the monitoring of targets of interest with sufficient frequency, continuity, accuracy, precision, spectral diversity, and data content that the targets will not be able to move or change substantially without notice.

Terrorism: an anxiety-inspiring method of repeated violent action, used by clandestine or semi-clandestine individual, group, or state actors for idiosyncratic, criminal, or political reasons, whereby—in contrast with assassination—the direct targets of violence are not the main targets. The immediate human victims of violence are generally chosen randomly (targets of opportunity) or selectively (representative or symbolic targets) from a target population and serve as message generators. Threat- and violence-based communication processes between terrorist (organization), (imperiled) victims, and main targets are used to manipulate the main target (audience(s)), turning it into a target of terror, a target of demands, or a target of attention, depending on whether intimidation, coercion, or propaganda is primarily sought (Schmid, 1988).