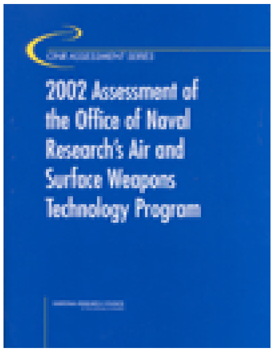

2002 Assessment of the Office of Naval Research's Air and Surface Weapons Technology Program

Committee for the Review of ONR's Air and Surface Weapons Technology Program, National Research Council

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Committee for the Review of ONR's Air and Surface Weapons Technology Program
Naval Studies Board
Division on Engineering and Physical Sciences
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Preface

The mission of the Office of Naval Research (ONR) is to maintain a close relationship with the research and development community to support long-range research, foster discovery, nurture future generations of researchers, produce new technologies that meet known naval requirements, and provide innovations in fields relevant to the future Navy and Marine Corps. Accordingly, ONR supports research activities across a broad range of scientific and engineering disciplines. As one means of ensuring that its investments appropriately address naval priorities and requirements and that its programs are of high scientific and technical quality, ONR requires that each of its departments undergo an annual review (with a detailed focus on about one-third of the reviewed department's programs). The Air and Surface Weapons Technology program reviewed in this report resides within the Strike Technology Division (Code 351) of the Naval Expeditionary Warfare S&T Department (Code 35) of ONR.

At the request of ONR, the National Research Council (NRC) established the Committee for the Review of ONR's Air and Surface Weapons Technology Program to review and evaluate discovery and invention (D&I) thrusts (ordnance, directed energy, gun weaponry, precision targeting and guidance, and propulsion and aeromechanics) and air and surface weapons objectives, components, and interfaces in two of ONR's Future Naval Capabilities (FNCs) programs (Time Critical Strike and Missile Defense). The committee selected the review criteria.

The committee met once, May 14-16, 2002, in Washington, D.C., to both gather information and prepare an initial draft report. The 3-day meeting was divided into two parts: The first comprised presentations by and interactions with project managers (and ONR-supported principal investigators) responsible for various program components, and the second was devoted to discussing the issues, developing consensus, and drafting the committee's findings and recommendations. (The committee members received reading material from the sponsor prior to the first meeting.) The committee's report represents its consensus views on the issues posed in the charge.

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:

Eugene E. Covert, Massachusetts Institute of Technology,
Jose B. Cruz, Jr., Ohio State University,
William A. Davis, Guntersville, Alabama,
Jack E. Goeller, Advanced Technology and Research Corporation,
Arthur H. Guenther, University of New Mexico,
Daniel N. Held, Northrop Grumman Corporation, and
Joseph Metcalf III, Washington, D.C.

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

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APPENDIXES

Executive Summary

BACKGROUND

The Office of Naval Research (ONR) contracted with the Naval Studies Board (NSB) of the National Research Council (NRC) to establish a committee to review ONR's Air and Surface Weapons Technology (ASWT) program.[1] The committee convened on May 14 and 15, 2002, and reviewed more than 20 science and technology (S&T) efforts that were presented as constituting the ASWT program. The committee then met separately on May 16, 2002, to formulate its findings and recommendations.[2] This report represents the consensus views of the committee and is based on the information presented prior to and at the review, as well as on the committee members' accumulated experience and expertise in military operations, systems, and technologies.

The ONR ASWT program resides within the Strike Technology Division (Code 351) of the Naval Expeditionary Warfare Department (Code 35). In 2002 the ASWT program is funded at $73.6 million, which is approximately 24 percent of the Strike Technology Division budget. As with all of ONR, the ASWT program began a major funding transition in FY02. Specifically, most of ONR's 6.3 funding (advanced development) and about half of its 6.2 funding (exploratory development) are now dedicated to 12 major program areas called Future Naval Capabilities (FNCs). The purpose of the FNCs is to focus advanced technology development at ONR on naval force capabilities that have been identified as having a high priority for the future by a cross-functional group of naval operators, naval development and support organizations, and ONR program managers. The remaining half of ONR's 6.2 funding and most of its 6.1 funding (basic research) are concentrated into discovery and invention (D&I) thrusts that will provide technologies, some of which will go into future FNCs. The ASWT 2002 budget is allocated as follows: (1) D&I at $19.9 million, (2) FNC at $36.5 million, and (3) other 6.2 and 6.3 at $17.2 million.[3]

[1]Biographies of committee members are given in Appendix A.

[2]The agenda for the 3-day meeting is presented in Appendix B. Also, it should be noted that no top-down exposition of critical Department of the Navy needs was presented to the committee.

[3]There are currently no ONR ASWT program efforts funded at the 6.1 level. Approximately $5 million is funded by Code 351 for 6.1 intelligent autonomy efforts.

The ASWT program was presented to the committee in five D&I thrust areas (ordnance, directed energy, gun weaponry, precision targeting and guidance, and propulsion and aeromechanics) and in the air and surface weapons aspects of one FNC (Time Critical Strike).[4] Several projects were presented within each D&I and FNC thrust area. Chapters 3 and 4 of this report cover these thrust areas, while Chapter 2 offers general observations and suggests new science and technology (S&T) areas for consideration by the ASWT program.

The committee reviewed only the elements of naval air and surface weapons S&T managed by the ASWT program in Code 351. Other significant contributing technologies, such as energetic materials, which are developed in the ONR Engineering, Materials, and Physical Sciences S&T Department (Code 33), and target tracking and sensor fusion, which are developed in the ONR Information, Electronics, and Surveillance S&T Department (Code 31), were not reviewed at this time. In some respects, therefore, the committee did not receive a complete picture of the state of naval air and surface weapons S&T.

ASSESSMENT OF THE ONR AIR AND SURFACE WEAPONS TECHNOLOGY PROGRAM

The committee's assessment and recommended actions for the ASWT program by thrust area are summarized in Table ES.1 and are discussed in Chapters 3 and 4. In general, the committee found the ASWT program to be reasonably well focused and clearly responsive to the FNC process. Even the D&I thrusts are clearly focused on supporting one or more FNCs in the longer term. The quality of the work that was briefed was generally high. The technical approaches were sound and the results often impressive, especially in light of the relatively modest funding levels.

Within the ASWT program as presented, the committee identified several excellent S&T projects that fully satisfied all of its evaluation criteria. The criteria selected by the committee, based on its experience in conducting similar reviews, included the appropriateness of the investment strategy within the context of Navy and Marine Corps priorities and requirements, impact on and relevance to Navy and Marine Corps needs, scientific and technical quality of the work, and progress by ONR since the 1999 review.[5]

However, the committee was concerned with other aspects of the ASWT program, namely the strong S&T focus on near-term needs and the occasional pursuit of S&T in isolation from future operational requirements. These areas of concern, including suggested new topics for consideration by the future ASWT program, are discussed below.

Balancing Near- and Long-Term Needs

While the FNC process for aligning and partnering the requirements, acquisition, and S&T communities appears in principle to be very successful in focusing S&T investments and creating a clear path

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[4]The study's terms of reference also call for the committee to review air and surface weapons aspects of the Missile Defense FNC. With the exception of the reactive materials project under the ordnance D&I thrust, the committee received no additional presentations or information relating to air and surface weapons aspects of the Missile Defense FNC.

[5]This is the second cycle in NSB's review of ONR's Air and Surface Weapons Technology Program; the first cycle was conducted in 1999 (Naval Studies Board, National Research Council. 1999. *1999 Assessment of the Office of Naval Research's Air and Surface Weapons Technology Program,* National Academy Press, Washington, D.C.).

for transition to acquisition within the future years' defense plan, it has done so by focusing ASWT program S&T almost exclusively on near-term air and surface weapons needs, to the detriment of developing technologies for the Navy and Marine Corps of the future. Moreover, FNCs emphasize transition rather than technology, and this is reflected in the ASWT program: (1) there is no 6.1 funding by Code 351 to address fundamental problems limiting performance and important program areas such as automatic target recognition (ATR), and (2) D&I thrusts are predictably being tailored to fit and align with FNCs.

Furthermore, there seems to be little or no systems analysis capability within the overall S&T planning process at ONR. While the committee was pleased to see the development of the enabling capabilities effort to serve as scenarios for some elements of the ASWT program (e.g., the Time Critical Strike (TCS) FNC), it was not apparent that any further analysis leveraged those enabling capabilities to increase understanding of the requirements for and merits of the technology being pursued. Also of concern was the committee's impression that some ASWT program efforts were not fully aware of synergistic opportunities presented by programs in the other Services: for example, the Army's heat capacity solid-state laser program and the U.S. Air Force-Swedish reactive materials program.

As a result of these concerns, the committee believes that a program realignment will be needed in Code 351 if future naval air and surface weapons technology is to have a balanced S&T investment portfolio so that it can meet both near- and long-term needs. In all three of its earlier assessments, NSB recommended in one form or another the need for systems analysis as part of an overall S&T planning process at ONR.[6] Most recently, in its 2001 assessment of ONR's Aircraft Technology program, NSB recommended that a long-range strategic plan be developed to provide (1) a framework for future ONR S&T investments, including emphasis on D&I, and (2) a vision for new capabilities, including advanced concepts at affordable costs. The committee believes that this earlier recommendation is applicable also to the ASWT program.

Recommendation: In collaboration with other Department of the Navy elements, ONR should develop a strategic naval air and surface weapons technology plan that will achieve a balance between near- and long-term goals. This effort should include collaboration with both the Marine Corps Combat Development Command and the Navy Warfare Development Command, given their concept-based approaches, as well as the help of the Office of the Chief of Naval Operations (OPNAV) and the Naval Air Systems Command (NAVAIR), given their influence on naval air and surface weapons technology needs. Such collaboration might even help to stimulate, evaluate, and transition new technologies to fleet experiments and expedite their transition to operational use. Moreover, systems analysis should be used as a means for developing this strategic plan as well as throughout the overall S&T planning process at ONR. Finally, as part of this strategic plan, the committee recommends that all projects relevant to an S&T air and surface weapons capability throughout ONR and the Department of the Navy be collectively reviewed, even though they exist in several functional organizations.

[6]Naval Studies Board, National Research Council. 1999. *1999 Assessment of the Office of Naval Research's Air and Surface Weapons Technology Program,* National Academy Press, Washington, D.C.; Naval Studies Board, National Research Council. 2000. *2000 Assessment of the Office of Naval Research's Marine Corps Science and Technology Program,* National Academy Press, Washington, D.C.; Naval Studies Board, National Research Council. 2001. *2001 Assessment of the Office of Naval Research's Aircraft Technology Program,* National Academy Press, Washington, D.C.

TABLE ES.1 Summary of Assessment and Recommended Actions for the ASWT Program

Technology Thrust	Appropriateness to Requirements	Relevance to USN/USMC Need	Scientific and Technical Quality of Work	Progress Since 1999 Review	Recommendations
Discovery and Invention Technology Thrusts					
Ordnance					• Incorporate reactive materials in penetrating fragments that are robust against countermeasures. Use modeling and simulation to better estimate time-space distribution of energetic release. • Conduct R&D effort to optimize composition of fieldable thermobaric explosive composition with any ACTD units delivered to be warfighters after operational, test, and evaluation safety review and analysis. • Continue to develop interactive experimental and calculational program to model thermal-event (cook-off) response of weapons with DOE laboratories. • Develop more tractable explosive composition for high-speed penetrating munitions in concert with the National Energetics Program.
Reactive materials	2	2	2	2	
Thermobaric weapons	2	2	2	5	
Survivability	2	2	2	5	
Directed energy					• Demonstrate capability to detect, identify, and acquire a target in high sea clutter and point a laser at very low elevations. • Conduct additional systems study of FEL scale-up uncertainties and of alternative operating wavelengths.
Pointing and tracking	3	3	2	5	
Rationale for FEL and alternatives	3	3	2	5	
Rationale for solid-state laser choices	3	3	3	5	
Propagation	3	3	3	5	

TABLE ES.1 Continued

Technology Thrust	Appropriateness to Requirements	Relevance to USN/USMC Need	Scientific and Technical Quality of Work	Progress Since 1999 Review	Recommendations
Nonlethal options for asymmetric threats	3	3	3	5	• Prepare historical summary to compare/contrast competing solid-state laser techniques with ONR choices. • Provide rationale for current approach of laboratory/propagation/simulation vis-à-vis existing body of theoretical/experimental knowledge. • Consider that the choice of 1-micron wavelength is not eye-safe. • Consider high-power microwaves against asymmetric threats.
Gun weaponry					• Complete but do not push for ranges greater than already demonstrated to avoid high risk in related areas such as barrel erosion. • Conduct systems analysis including logistics. • Explore solid rocket-propelled ballistic missiles for longer-range fire missions. • Consider that low-cost, high-acceleration, precision-guidance work has broad utility and should be continued.
Projectiles and gun launchers	3	2	2	5	
Guidance for projectiles	1	1	1	1	
Precision targeting and guidance	2	2	2	2	• Direct greater effort toward integrating data from disparate sources, and use of the fused data to accelerate decision making. • Continue and augment current program with appropriate 6.1 funds.

continues

TABLE ES.1 Continued

Technology Thrust	Appropriateness to Requirements	Relevance to USN/USMC Need	Scientific and Technical Quality of Work	Progress Since 1999 Review	Recommendations
Precision targeting and guidance (continued)					• Continue and augment the current program, which also may benefit missile programs in the strike area. • Coordinate with other DARPA/Service programs.
Propulsion and aeromechanics					• Initiate/stimulate program toward better high-temperature structural integration analysis. • Ensure that producibility and materials costs are considered in concept design decisions to get an acceptable cost per round. • Consider producibility and unit cost as key factors. • Document breakthrough that led to solution of the nozzle erosion problem. • Continue this nationally well-integrated work.
Hypersonic weapon technology	2	2	2	2	
Integrated high-payoff rocket technology	2	2	2	5	
Time-critical Strike Technology Thrusts					
Cruise missile real-time retargeting	2	2	3	2	• Devote more effort to verification of ATR algorithm that is selected for inclusion in the weapon. • Plan eventual integration of product of WIL thrust if that is successful.
Image and video analysis	2	2	3	2	• Complete on present schedule. Possibly, accelerate battle damage assessment work. • Coordinate with related USAF and NRO efforts.

TABLE ES.1 Continued

Technology Thrust	Appropriateness to Requirements	Relevance to USN/USMC Need	Scientific and Technical Quality of Work	Progress Since 1999 Review	Recommendations
Enhanced target acquisition and location system	2	2	2	2	• Continue the present program to transition.
Precision strike navigation	1	1	1	2-1	• Pursue to successful completion reduced-cost, accurate inertial instruments.
Mission responsive ordnance	1	1	2	2	• Complete work on current payload. • Consider use of miniaturized proximity fuzes on submunition.
High-speed antiradiation demonstration	2	2	2	2	• Complete to transition as part of the development of the HSARM under PMA-242 sponsorship.
Weapons imagery link	1	1	1	2	• Complete to scheduled transition to provide a high-performance modern replacement for the AWW-13 data link.
Advanced gun barrel technologies	3	3	3	5	• Develop and validate scaling laws for fatigue life and erosion rates that will permit small-scale model data to be extrapolated to full scale. • Utilize existing Air Force databases and expertise on fatigue of metal matrix composites in selection of materials, processing techniques, and integrated barrel designs.

NOTE: 1 = Excellent; 2 = Good; 3 = Fair; 4 = Poor; 5 = Not Applicable. Acronyms used are defined in Appendix C.

Responding to Future Operational Requirements

The committee's first review criterion was the appropriateness of the ASWT program investment strategy within the context of Navy and Marine Corps priorities and requirements. In many thrust areas (e.g., precision strike navigation and cruise missile real-time retargeting), the ASWT program seemed to be responsive to operational requirements, while in other areas (e.g., gun weaponry and directed energy) there seemed to be a much weaker connection between the technology and the naval requirement.

In the gun weaponry area, the NSB's 1999 assessment of the ASWT program pointed out the obvious application and advantage of solid-rocket-propelled weapons at the longer ranges in lieu of trying to push gun-launched rocket-assisted projectiles or extended-range guided munitions (ERGMs) to distances that would entail many other problems (e.g., erosion and logistics). The committee was told that there are two obstacles to the use of solid-rocket weapons for volume fire support: (1) the inability to provide an at-sea reload capability and (2) the limited number of launchers and the limited magazine space available onboard most surface combatants. In the committee's view, both of these obstacles are surmountable.

Recommendation: ONR should consider funding a significant D&I effort and a related analysis to address the emerging need for rockets for naval fire support. This future program should have the following components:

- A new family of stowage and launching canisters that will allow cold launch steam or compressed-gas ejection of rocket-launched weapons from existing vertical launch system (VLS)-equipped combatants as well as from specialized new combatants.
- A solid-rocket weapon that builds on the integrated high-payoff rocket propulsion technology (IHPRPT) thrust and the excellent microelectromechanical systems (MEMS) precision-guidance work now being pursued by Code 351. Such weapons, cold-launched, could be carried by other types of combatants such as the littoral combat ship now in the concept development stage.
- A systems development and analysis effort addressing at-sea reload in the context of a specialized large-magazine ship capable of both resupply and direct launch of weapons.

Recommended New Program Areas

The committee suggests four new program areas for ONR's consideration in the future ASWT program. The topics range from basic research to advanced technologies.

Compelling Problems of the Time Critical Strike FNC

The committee believes that, overall, the TCS FNC does not aggressively address some of the more urgent problems of time-critical strike. Areas that need to be investigated include the following:

- Improved decision aids that will accelerate the required analyses of the potential for collateral or unintended damage that must accompany each target nomination before weapon release can be authorized for a given target.
- Improved sensor systems and processing algorithms to allow more efficient discrimination between targets and decoys and between military and civil targets.

- New or expanded concepts of operation (CONOPS) and new command, control, and targeting systems for loitering weapons and the platforms (e.g., UCAVs) that might carry them.
- New or expanded CONOPS for a precision, high-speed, surface-to-surface weapon that can reach its intended target from long standoff distances in times that are short compared with the dwell times of mobile or relocatable targets.
- A more systems-oriented approach to the target recognition–weapon assignment chain by considering all potential sources of data that can be applied and robust means of fusing those data for effective and rapid correlation of scenes and viewpoints as they change with time. There exist tools and capabilities that should be but are not being applied to the current work, which is focused on today's weapon system CONOPS.

Offense-Defense Coordination and Deconfliction

Based on the information presented to the committee, Code 351 has no current or future efforts aimed at addressing offense-defense coordination and deconfliction. In many situations, the advantages of the systems that Code 351 is developing will be negated unless better coordination is achieved. Accordingly, the committee recommends that ONR, in collaboration with the appropriate Department of the Navy offices, undertake to develop the technical means and CONOPS by which the Navy and Marine Corps could achieve the coordination necessary for expeditionary warfare, even in the absence of such means at the Joint level and in the other Services.

Asymmetric Threats

The committee was briefed on concerns about asymmetric threats and the special requirements imposed by them. A clear need is layered defense with a high probability of single-shot, single-burst kill using multispectral acquisition and tracking. Of particular interest in light of the constraints on rules of engagement would be the application of nonlethal concepts that are currently in development in other Services, discussed in Chapter 3 under "Directed Energy." The committee recommends investigating some nonlethal approaches in future Code 351 programs, or, at a minimum, integration of nonlethal approaches into systems in coordination with Code 353 (Expeditionary Operations Technology Division).

Automatic Target Recognition Fundamentals

Advantage should be taken of multispectral imaging, special-purpose array processors designed for high-speed scene-to-scene correlation, and commercially available high-speed terrain-rendering engines to create common viewpoints for images from multiple sensor platforms.

There are many areas of fundamental research that could have considerable impact but that were not briefed. Even if these areas are addressed elsewhere in ONR, their omission from the Code 351 agenda slows the pace with which they might be incorporated into FNCs. The committee recommends that in cooperation with other relevant ONR activity, Code 351 accelerate the automatic target recognition program area.

1

Introduction

CONTEXT

The Office of Naval Research's (ONR) Air and Surface Weapons Technology (ASWT) program resides within the Strike Technology Division (Code 351) of the Naval Expeditionary Warfare Science and Technology Department (Code 35). In 2002 the ASWT program is funded at $73.6 million, which is approximately 24 percent of the Strike Technology Division budget. Like all of ONR, the ASWT program began a major funding transition in FY02, when most of ONR's 6.3 funding (advanced development) and about half of its 6.2 funding (exploratory development) were dedicated to 12 major program areas called Future Naval Capabilities (FNCs). The purpose of the FNCs is to focus advanced technology development at ONR on naval force capabilities that have been identified by a cross-functional group of naval operators, naval development and support organizations, and ONR program managers as having a high priority for the future. The remaining half of ONR's 6.2 funding and most of its 6.1 funding (basic research) are concentrated into discovery and invention (D&I) thrusts that will provide technologies, some of which will go into future FNCs. The ASWT 2002 budget is divided as follows: (1) D&I at $19.9 million, (2) FNC at $36.5 million, and (3) other 6.2 and 6.3 at $17.2 million.[1] Code 351 provided current and projected budget figures through FY03 for each of these areas (Table 1.1).[2]

The goals of the ASWT program are to develop and transition enabling air and surface weapons technologies that provide the fleet affordable conventional weapons systems capable of meeting the need for upgrades of today's air and surface weapons and that lay the foundation for weapons of

[1]There are currently no ONR ASWT program efforts funded at the 6.1 level. Approximately $5 million is funded by Code 351 for 6.1 intelligent autonomy efforts.

[2]This information was provided at the end of the meeting, making it difficult to understand the level and detail of resources applied to air and surface weapons within ONR and throughout the Department of the Navy. While the read-ahead material provided adequate technical insight into the program of record, it did not provide an adequate framework for which the technical program was funded upon.

TABLE 1.1 ONR 351 Air and Surface Weapons Technology Program Budget Through FY03 (millions of dollars)

	2000		2001		2002			2003		
Area	6.2	6.3	6.2	6.3	D&I	FNC	Other 6.2/6.3	D&I	FNC	Other 6.2/6.3
Ordnance	7.1	4.4	7	4.7	1.8	6.9	4.7	1.8	8.8	15
Directed energy	0	0	0	0	1	5	0	1.9	0	0
Guns	0.4	0	0.8	0	0.2	0	0	0.4	1.2	0
Projectiles (guns)	0	2	0	0	4.9	0	0	0.5	0	0
Launchers	0	5.1	0	5	0	0	0	0.5	0	0
Guidance and control	4.4	14.4	4.4	4.2	1	11.7	0	1.2	14.5	0
Targeting	7.5	0.7	7.5	0.9	1.7	11.4	0	0.6	13.6	0
Systems technology investigations	2.4	0	3.2	0	1	0	0	0	0	0
Propulsion	3.2	2.7	3.3	4.3	7.7	1.5	7.5	5.7	8.5	10
Airframes (hypersonics)	2.2	0	2.7	0	0.6	0	5	0	0	10
Subtotal	27.2	29.3	28.9	19.1	19.9	36.5	17.2	12.6	46.6	35
TOTAL FOR YEAR	56.5		48.0		74.2			94.2		

SOURCE: Graff, Gil Y., Office of Naval Research. 2002. Vugraph, "Air and Surface Weapons Investment by Technology Area Thrusts: Categories," in *Air and Surface Weapons Technology Program Overview*, briefing to the committee on May 14.

TABLE 1.2 ONR 351 Air and Surface Weapons Technology Thrust Objectives

Thrust	Objective
D&I Thrust	
Ordnance	To improve the performance of tactical ordnance through the use of reactive energetic materials that increase lethality and enhance kill assessment and to develop adaptive dial-a-yield ordnance that can adapt to various target types with the same munition.
Directed energy	An area just recently reactivated after a 10-year hiatus to evaluate the advances in free electron laser technology applications to the Navy in the marine environment.
Gun weaponry	To develop a broadly applicable technology base for affordable long-range precision gun weapons to support Marine expeditionary operations.
Precision targeting and guidance	To develop technologies that will improve the performance of tactical airborne and shipboard weapon fire control systems, including better methods for fusing imagery from different sources and improving the ability to provide digital elevation data with sufficient resolution for correlating imagery from various types of imaging sensors.
Propulsion and aeromechanics	To demonstrate the critical technologies required for a Mach 5 to 6 air-breathing strike weapon with a range of 400 to 700 nm carrying penetrating ordnance (hypersonic weapons technology program) and to establish a national rocket propulsion technology development and demonstration program with participation by Department of Defense, the National Aeronautics and Space Administration, and industry to provide revolutionary advancement in rocket propulsion performance and operational capabilities (integrated high-payoff rocket propulsion program).
TCS FNC Thrust	
Cruise missile real-time retargeting	To develop the technology for cruise missile LADAR seekers and to accurately target or divert weapons to time-critical targets at low cost.
Image and video analysis	To reduce the time required to exploit tactical imagery from SHARPs and Global Hawk-type surveillance systems for targeting and damage assessment of time-critical relocatable targets.
Enhanced target acquisition and location system	To provide an improved and lower cost target locating capability for forward observers and forward air controllers employing a gyrocompass and eye-safe laser range finder/illuminator.
Precision strike navigation	To demonstrate a hybrid module for the electro-optical portion of an interferometric fiber optic gyro that will radically reduce the cost of these devices for tactical weapons while retaining the accuracy.
Mission responsive ordnance	To develop and demonstrate ordnance and dispensing technology that will enable a single cruise missile payload to act as a unitary weapon, an area weapon, or a multiple discrete target killer.
High-speed antiradiation demonstration	To demonstrate an increased-performance ducted rocket and steering system compatible with the advanced antiradiation guided missile and suitable for transition to system development demonstration.
Weapons imagery link	To develop and demonstrate an improved data link for imagery-guided weapons such as SLAM (ER), including antijam increased data throughput and reduced latency.
Gun barrel erosion (and fatigue)	To develop next-generation gun barrel design solutions to increase barrel life and performance for higher-performance, naval gun-launched munitions by use of refractory coatings and composite barrel materials.

NOTE: Acronyms used are defined in Appendix C.

tomorrow. Within the ASWT program, technology investments are concentrated into five D&I thrusts (ordnance, directed energy, gun weaponry, precision targeting and guidance, and propulsion and aero-mechanics) and into the air and surface weapons aspects of one FNC—Time Critical Strike (TCS). The objectives of these thrusts are summarized in Table 1.2.

The stated S&T investment strategy for Code 351 is to select and support crucial S&T that provide evolutionary or revolutionary solutions to aircraft, air- and surface-launched weapons, and advanced sensor systems.

The committee was charged with evaluating the ASWT program represented by more than 20 individual efforts that were presented over 2 days, May 14 and May 15, 2002. The committee selected the following evaluation criteria based on its experience in conducting similar reviews:

- Appropriateness of the investment strategy within the context of Navy and Marine Corps priorities and requirements;
- Impact on and relevance to Navy and Marine Corps needs;
- Scientific and technical quality of the work; and
- Progress by ONR since the 1999 review.[3]

The committee was also asked to recommend new areas that should be considered for inclusion in future ASWT program activities.

ORGANIZATION OF THIS REPORT

In Chapter 2, the committee provides some general observations on the future of naval air and surface weapons technology and on the ASWT program. Chapters 3 and 4 pertain to the D&I and FNC thrust areas, respectively. Each begins with an overview of the thrust and then proceeds to the findings and recommendations for each project presented to the committee at its May 2002 meeting.

[3]This is the second cycle in NSB's review of ONR's Air and Surface Weapons Technology program; the first cycle was conducted in 1999 (Naval Studies Board, National Research Council. 1999. *1999 Assessment of the Office of Naval Research's Air and Surface Weapons Technology Program,* National Academy Press, Washington, D.C.).

2

General Observations

OVERALL ASSESSMENT

The committee found the overall ASWT program, as presented, to be reasonably well focused and clearly responsive to the FNC process. Even the D&I thrusts clearly focus on supporting one or more FNCs in the longer term. Furthermore, the quality of the work appeared high, the technical approaches were generally sound, and the results were often impressive, especially in light of the relatively modest funding levels.[1] The committee identified several excellent S&T projects that fully satisfied all of the evaluation criteria established. These projects—guidance for projectiles, precision strike navigation, and weapons imagery link—were of high technical quality and appeared to be led by technically competent managers.[2] The committee recommends that these excellent projects be continued and that sufficient funding, acknowledgment, and ongoing support be provided to ensure their successful transition into major programs.

The committee had some general observations on the future of naval air and surface weapons that overarch the specific findings and recommendations, which follow in Chapters 3 and 4 of this report. In particular, the committee was concerned with the ASWT program's strong S&T focus on near-term needs and the occasional pursuit of S&T in isolation from future operational requirements. These concerns are discussed in the next two sections, and new topics suggested for consideration in the future ASWT program are discussed in the last section of the chapter.

[1]It was noted during presentations to the committee that revenue from patents is a significant source of funding for the Naval Research Laboratory (NRL). To the extent that this finding can be validated, it is an interesting and impressive measure of the success of NRL in its D&I effort. While other elements of ONR might have less opportunity to follow the lead of NRL (and academia) in aggressively seeking patents and collecting royalties and licensing fees on those patents, the committee, nevertheless, believes there may be similar opportunities to enhance the overall D&I portfolio.

[2]Guidance for projectiles is an effort under the D&I gun weaponry thrust; the precision strike navigation and weapons imagery link efforts are found under the Time Critical Strike FNC.

BALANCING NEAR- AND LONG-TERM NEEDS

As noted in Chapter 1, ONR began a major funding transition in FY02, when it attempted to bridge the gap between long-term "technology push" research (D&I) and short-term "requirement pull" development (fleet/force initiatives). The current approach to bridging this gap is the FNC process, which attempts to provide a smooth transition across the mismatch between the technologists and the requirements and acquisition communities, all of whom participate in the integrated product team overseeing each FNC.

While the FNC process for aligning and partnering these communities appears in principle to be very successful in focusing S&T investments and creating a clear path for transition to acquisition within the future years' defense plan, it has done so through an almost exclusive ASWT program S&T focus on air and surface weapons near-term needs, to the detriment of developing technologies for the Navy and Marine Corps after next. Moreover, FNCs focus on transition rather than technology, and this is reflected in the ASWT program as follows: (1) there is no 6.1 funding by Code 351 to address fundamental problems, limiting performance and important program areas such as automatic target recognition (ATR) and (2) D&I thrusts are predictably being tailored to fit and align with FNCs.[3]

Furthermore, there seems to be little or no systems analysis capability within the overall S&T planning process at ONR. While the committee was pleased to see the development of the enabling capabilities effort to serve as scenarios for some aspects of the ASWT program (e.g., TCS FNC), it was not apparent to the committee that any further analysis leveraged those enabling capabilities to understand the requirements for and merits of the technology being pursued. For example, attempting to increase gun ranges using large, double-tamped propulsive loads bothered the committee in that no systems analysis had been conducted to evaluate the utility and systems feasibility of such an effort.[4] Also, of concern was the committee's impression that some ASWT program efforts were not fully aware of synergistic opportunities presented by programs in other Services; for example, the U.S. Army heat-capacity lasers and the U.S. Air Force and government of Sweden programs in reactive materials.

As a result of these concerns, the committee believes that a program realignment will be needed in Code 351 if future naval air and surface weapons technology is to have a balanced S&T investment portfolio so it can meet both near- and long-term needs. In all three of its earlier assessments, NSB recommended in one form or another the need for systems analysis as part of an overall S&T planning process at ONR.[5] Most recently, in its 2001 assessment of ONR's Aircraft Technology program, NSB

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[3]The strategic choices made in selecting the largely 6.2 and 6.3 activity pursued by Code 351 means that the activity (from a technology standpoint at least) has a good chance of eventual deployment by the fleet; however, no ONR ASWT program efforts are being funded at the 6.1 level, and only $5 million of Code 351 aircraft funding is allocated for intelligent autonomy efforts. Interestingly, some of this 6.1 effort now being incorporated into the Autonomous Operations FNC appears to derive from small business independent research (SBIR) and independent research and development efforts. Nevertheless, the ASWT program's direct links to 6.1 appear to be relatively modest, beyond a general awareness that 6.1 research or its equivalent is often the ultimate source of transformational technology.

[4]Another example relates to the D&I thrust directed energy. There are many system and operational issues that must be considered for shipboard free-electron laser directed-energy weapon, including radiation and electrical power and volume requirements. The current program is aimed at demonstrating the feasibility of a scale-up to the 100-kW level, along with studies of radiation management and electrical power requirements.

[5]Naval Studies Board, National Research Council. 1999. *1999 Assessment of the Office of Naval Research's Air and Surface Weapons Technology Program,* National Academy Press, Washington, D.C.; Naval Studies Board, National Research Council. 2000. *2000 Assessment of the Office of Naval Research's Marine Corps Science and Technology Program,* National Academy Press, Washington, D.C.; Naval Studies Board, National Research Council. 2001. *2001 Assessment of the Office of Naval Research's Aircraft Technology Program,* National Academy Press, Washington, D.C.

recommended that a long-range strategic plan be developed to provide (1) a framework for future ONR S&T investments, including emphasis on D&I and (2) a vision for new capabilities, including advanced concepts at affordable costs. The committee believes that this earlier recommendation remains applicable today.

Recommendation: In collaboration with other Department of the Navy elements, ONR should develop a strategic naval air and surface weapons technology plan that will achieve a balance between near- and long-term goals. This effort should include collaboration with both the Marine Corps Combat Development Command and the Navy Warfare Development Command, given their concept-based approaches, as well as the help of the Office of the Chief of Naval Operations and the Naval Air Systems Command, given their influence on naval air and surface weapons technology needs. Such collaboration might even help to stimulate, evaluate, and transition new technologies to fleet experiments and expedite their transition to operational use. Moreover, systems analysis should be used as a means for developing this strategic plan as well as throughout the overall S&T planning process at ONR. Finally, as part of this strategic plan, the committee recommends that all projects relevant to an S&T air and surface weapons capability throughout ONR and the Department of the Navy be collectively reviewed, even though they exist in several functional organizations.

RESPONDING TO FUTURE OPERATIONAL REQUIREMENTS

The committee's first review criterion was the appropriateness of the ASWT program investment strategy within the context of Navy and Marine Corps priorities and requirements. In many thrust areas (e.g., precision strike navigation and cruise missile real-time retargeting), the ASWT program seemed to be responsive to operational requirements, while in other areas (e.g., gun weaponry and directed energy) there seemed to be a much weaker connection between the technology and the naval requirement.

An important example of a requirement is that for naval fire support. The committee was told that the projected concept of operations (CONOPS) for naval fire in support of Marine forces requires deep, accurate, high-rate, high-volume delivery of ordnance inserted as far inland as 200 nautical miles (nmi). These airborne units would not carry artillery for volume fire. Most targets will be time critical for one reason or another. Once the process time from surveillance to target detection, identification, and assignment is reduced, there are two basic ways to provide support fire and reduce the time to weapons on the target: the first is to minimize the weapon flight time from launch platform to target, the second is to loiter the launch platform or weapon close to the expected target-rich area. Almost all current Code 351 time-critical and precision-strike technology programs are focused on the second approach using cruise missiles or aircraft/uninhabited combat air vehicle (UCAV)-launched weapons. Two exceptions are the gun weaponry thrust, which is applicable to ranges of not much more than 50 nmi, and the hypersonic weapons technology project (under Propulsion and Aeromechanics), aimed at ship- and air-launched Mach 5 or 6 air-breathing cruise missiles with ranges in excess of 400 nmi.

The difficulty with the current emphasis on loitering weapon platforms or weapons for long-range TCS is limited payload capacity and limited endurance. The Navy has the ability to position platforms with very long endurance and with capacity for large volumes of sustainable fire in support of expeditionary forces deployed from the fleet.

The NSB's 1999 assessment of the ASWT program pointed out the obvious application and advantage of solid-rocket-propelled weapons at the longer ranges in lieu of trying to push gun-launched rocket-assisted projectiles or extended-range guided munitions (ERGMs) to ranges that would introduce many other problems (e.g., erosion and logistics). The committee is aware that the Naval Sea Systems Command (NAVSEA) is working on a naval version of the Army tactical missile system but believes this would offer only an interim and limited capability. The committee was told that there are two obstacles to the use of solid-rocket weapons for volume fire support: (1) the inability to provide an at-sea reload capability and (2) the limited number of launchers and the limited magazine space available onboard most surface combatants. In the committee's view, both of these obstacles are surmountable. Any long-range volume fire from surface ships will require solutions to both problems, yet there is now very little visible work under way to develop the required technology. Some high-payoff technology is sorely needed in this area.

The committee believes that ONR should take the initiative for some imaginative D&I work and analysis on ship-launched missile and stowage/launch concepts for the longer-range fire-support role. As one example, it is estimated that based on a propellant with a specific impulse (Isp) of 265 sec and a mass fraction of 0.85, a single-stage 9-in.-diameter missile less than 10 ft long with a launch gross weight less than 360 lb can accurately deliver a warhead equivalent to a 155 mm gun-launched projectile weighing about 90 lb to a distance of almost 200 nmi in less than 5 minutes. If a four-pack stowage and launch canister can be designed for individual missile cold launch and empty canister jettison, a stack of two four-pack canisters would fit in each existing vertical launch system (VLS) position.[6] If, say, 32 of 64 VLS positions were assigned for fire support, there would be 256 (32×8) rounds in firing position exclusive of other magazine capacity. A single tier of these launch modules would be ideal for the fast littoral combat ship concept. A second example is a 21-in.-diameter, two-stage missile using the existing type canister and Mk 72 booster as its first stage and the 21-in.-diameter second stage currently under consideration for Standard Missile, third generation (SM-3) growth options. Such a missile with a launch gross weight (LGW) of 5,900 lb could deliver 1,400 lb of munitions to a distance of 375 miles (600 km) in less than 7 minutes. (This LGW is substantially greater than current Standard Missiles and would have to be examined for handling and plenum compatibility.)

Advances in rocket-propelled gun-launched projectiles have been impressive, providing ranges in excess of 50 nmi. Attendant to these achievements has been the development of microelectromechanical system (MEMS) inertial components and Global Positioning System (GPS) elements that appear capable of withstanding the gun launch environment. However, the committee believes, as it did in the 1999 review, that a longer range should not be sought for this technology. Longer-range fire missions are probably better handled by solid-rocket-propelled ballistic missiles. While the attendant barrel erosion problems, setback acceleration requirements, and logistic issues of a gun round that is more than 10 ft long (and requires double tamp loading) are interesting to work on, in the committee's view they are barriers to effective use in the longer range fire-support role.

It should be mentioned that two of the arguments used to justify pushing gun technology to provide fire support at ranges in excess of 100 nmi are the limited magazine space aboard combatants and the inability to replenish missiles at sea. Several presentations indicated that the Navy cannot reload a VLS

[6]The committee believes the cold launch of shipboard missiles provides additional flexibility and firepower. This capability, a variant of the system used for years in ballistic missile submarines, nuclear powered (SSBN) offers several advantages. One scheme would employ a gas generator and water reservoir in each canister to generate the steam pulse to eject the weapon. Such a capability would allow much more flexible ship configurations without the plenum requirements currently needed for VLS-based weapons. It would also allow weapon mixes with easier reload capability. Canted launchers could protect the ship from post-eject fallbacks and would allow stacking canisters within the same real estate, jettisoning spent containers or hang fires (missiles not obeying firing instructions) to allow access to lower weapon canisters if firing order is top missiles first.

at sea. The committee is concerned that Code 351 assumes that this situation must continue. (In the 1960s, the FAST (fast automatic shuttle transfer) system was built and installed, but later abandoned owing to its complexity and many failures. These problems created a valid skepticism about such capabilities, but today's automation technologies offer solutions to many of the problems encountered back then.) While this is a logistics issue not directly in the purview of the ASWT program, it limits the program's choices. Today, it certainly affects the Navy's ability to provide sustained fire support with missiles. In the long term, the committee believes there will be an increasing need to use ship-based missiles for sustained strike and fire-support missions. To this end, the present limitations on at-sea missile reloading must be overcome. The committee believes, based on prior Navy work, that at-sea VLS reloading would be technically and economically feasible.[7]

Recommendation: ONR should consider funding a significant D&I effort and a related analysis to address the emerging need for rockets for naval fire support. This future program should have the following components:

- A new family of stowage and launching canisters that will allow cold launch steam or compressed-gas ejection of rocket-launched weapons from existing VLS-equipped combatants as well as from specialized new combatants. This effort should consider developing the ability to launch a volume-limited 21-in.-diameter, 21-ft-long missile round. It should also consider a configuration that would allow individual launch in the same manner of four 9-in.-diameter, 10-ft-long weapons.
- A solid rocket weapon that builds on the integrated high-payoff rocket propulsion technology (IHPRPT) thrust and the excellent microelectromechanical systems (MEMS) precision-guidance work now being pursued by Code 351. This additional effort would investigate rocket-launched weapons of the type mentioned above to meet the future Marine Corps deep fire support requirements. Such weapons, cold-launched, could be carried by other types of combatants such as the littoral combat ship now in the concept development stage. A littoral fire support ship would be an interesting adjunct to the cold launching of weapons discussed above. Such a ship carrying a large number and mix of solid-fueled missiles and weapons in various sizes along with the self-defense weapon systems of other combatants could serve as an at-sea resupply ship for other combatants as well as a weapon launcher self-directed or from Aegis ships via cooperative engagement capability (CEC). Such a ship would be large enough to support positive handling schemes that might allow safe at-sea transfer and emplacement of larger weapons. The small, fast littoral combat ship concept could take advantage of this reload capability as could guided missile destroyers (DDGs) and other Aegis platforms.
- A systems development and analysis effort addressing at-sea reload in the context of a specialized large-magazine ship capable of both resupply and direct launch of weapons. Such a capability would be valuable for sustained support of expeditionary forces in many scenarios. A littoral fire support ship with large magazines and many more launch positions could provide high-rate, high-

[7]For several years, the Naval Surface Warfare Center's (NSWC's) Port Hueneme Division has demonstrated a transportable rearming method (TRAM), estimated to be capable of reloading a VLS at a rate of 15 missiles/hr in sea state 5. In its 1997 *Technology for Future Naval Forces* study, the NSB stated that whether or not TRAM proves to be a satisfactory solution, the Navy should find some system for at-sea reloading (Naval Studies Board, National Research Council. 1997. *Technology for the United States Navy and Marine Corps, 2000-2035: Volume 8: Logistics*, National Academy Press, Washington, D.C., p. 14).

volume, long-range fire support. With more deck area, it might also provide a stable base for facilitating at-sea replenishment of new cold-launched weapons as well as existing VLS canister designs.

RECOMMENDED NEW PROGRAM AREAS

The committee suggests four new program areas for ONR's consideration in the future ASWT program. The topics range from basic research to advanced technologies.

Compelling Problems of the Time Critical Strike FNC

As discussed in Chapter 4, the committee believes that none of the TCS FNC thrusts are likely to fail to achieve their objectives. Most appear to have a high probability of a successful transition into the acquisition process. However, while the TCS FNC thrusts appear to address specific limitations of current systems (or, in the case of gun technology, future gun systems), the committee was disappointed with the TCS FNC overall, because it does not aggressively address some of the more urgent problems of time-critical strike. Areas that need to be investigated include the following:

- Improved decision aids that will accelerate the required analyses of the potential for collateral or unintended damage that must accompany each target nomination before weapon release can be authorized for a given target.
- Improved sensor systems and processing algorithms to allow more efficient discrimination between targets and decoys and between military and civil targets.
- New or expanded CONOPS and new command, control, and targeting systems for loitering weapons and the platforms (e.g., UCAVs) that might carry them.
- New or expanded CONOPS for a precision, high-speed, surface-to-surface weapon that can reach its intended target from long standoff distances in times that are short compared with the dwell times of mobile or relocatable targets.
- A more systems-oriented approach to the target recognition–weapon assignment chain by considering all potential sources of data that can be applied and robust means of fusing those data for effective and rapid correlation of scenes and viewpoints as they change with time. There exist tools and capabilities that should be but are not being applied to the current work, which is focused on today's weapon system CONOPS.

Offense-Defense Coordination and Deconfliction

Based on the information presented to the committee, Code 351 has no current or future efforts aimed at addressing offense-defense coordination and deconfliction. It is widely known that conflicts in the use of airspace will arise in intense actions, yet the doctrine necessary to help commanders resolve the conflicts has not yet been defined either by the Joint Chiefs of Staff (JCS) or by the Joint Theater Air and Missile Defense Organization (JTAMDO). Nevertheless, if the Navy and Marine Corps are to conduct expeditionary warfare successfully, their actions will need to be coordinated to avoid fratricide and other unintended effects. In many situations, the payoffs of the systems that Code 351 is developing will be negated unless better coordination is achieved. Accordingly, the committee recommends that ONR, in collaboration with the appropriate Department of the Navy offices, undertake to develop the technical means and CONOPS by which the Navy and Marine Corps could achieve the coordination necessary for expeditionary warfare, even in the absence of such means at the Joint level and in the other

Services. The CEC, as it evolves with upgrades which integrate the surveillance aircraft (E-2C), offers a framework for providing the connectivity for a naval single integrated air picture and presumably could integrate Marine ground units as well to achieve total theater situational awareness.

Asymmetric Threats

The committee was briefed on concerns about asymmetric threats and the special requirements imposed by them. While the need for improved ship defense against asymmetric threats within the constraining environment of foreign waters was clearly conveyed, there was only a tenuous connection to activity in Code 351 thrusts. Layered defense is clearly needed with high probability of single-shot, single-burst kill using multispectral acquisition and tracking. One area that appeared to be directly applicable to the problem of small-boat or jet-ski targets coming out of the sun was the infrared sea clutter rejection work. Of particular interest in light of the constraints on rules of engagement within ports of call would be the application of nonlethal concepts that are currently in development in other Services, discussed in Chapter 3 under "Directed Energy." The committee recommends investigating some nonlethal approaches in future Code 351 programs, or, at a minimum, integration of nonlethal approaches into systems in coordination with Code 353 (Expeditionary Operations Technology Division).

Automatic Target Recognition Fundamentals

The ASWT program-related efforts encompassing automatic target recognition (ATR) appeared to be focused on a valid near-term need—the ability to reduce the time from the acquisition of surveillance data from single-spectrum sensor assets to verified target recognition, validation for a strike decision, and then tasking the shooter in a form that the shooter can correlate with an aim point or what he/she will see as he/she approaches the target. There are four key problems with the specific application presented to the committee—the processing of F-18-carried shared advanced reconnaissance pod (SHARP) sensor data correlated with Global Hawk data to identify and assign targets in a cluttered environment. First is the correlation and fusion of area scenes from different sensors with different viewing angles, distances, optical and radio frequency (RF) spectrums, resolution, and display media. Second is the discrimination of potential objects of interest from normal terrain and vegetation, especially when camouflaged, based on unique signature characteristics. Third is placing those objects in the context of the area to determine combat identification for a strike decision, and fourth is providing the strike mission plan together with the data necessary for the shooter to approach, properly designate, and engage the target. The sense of the committee was that the recognition problem was being approached somewhat in isolation and without considering other parts of the system chain. In particular, advantage should be taken of multispectral images, special-purpose array processors designed for high-speed scene-to-scene correlation, and commercially available high-speed terrain-rendering engines to create common viewpoints for images from multiple sensor platforms.

In summary, ATR under harsh, deceptive, and dynamic environments remains a distant goal under Code 351 programs. There are many areas of fundamental research in other ONR programs that could have considerable impact, but they were not briefed to the committee. Even if they are addressed elsewhere, their omission from the Code 351 agenda slows the pace with which they might be incorporated into FNCs. The committee recommends that in cooperation with other relevant ONR activity, Code 351 accelerate the ATR program.

3

Discovery and Invention Technology Thrusts

ORDNANCE

Overview

Ordnance as defined by ONR refers only to the warhead component of a munition such as a missile- or gun-launched projectile. The other aspects of a munition are reported elsewhere. These include the guidance and control and propulsion and fuzing. However, it must be recognized that there is a complex relationship between ordnance and all the other attributes of a munition. For example, hypersonic propulsion enables the munition to reach the target in much shorter times and provides the velocity for deeper penetration into hard and deeply buried targets. Similarly, improved guidance and control allow lethality to be achieved by precisely delivering the warhead on or very close to the target rather than increasing the size and explosive content of the warhead.

Effort in the adaptive ordnance area is devoted to advancing warhead technologies to achieve better effectiveness. This is to be done by achieving higher energy levels for the warhead and by devising novel ways of applying the energy to targets, both of which are expected to lead to more rapid mission execution with less ammunition expended. The "adaptive" characteristic apparently refers to the idea that the explosive yield can be controlled to suit target type and engagement scenario. Work on achieving directional control of warhead effects based on information received from fuzing sensors was not mentioned, so is assumed to be taking place in other parts of the ONR program. The scope of the effort extends beyond adaptive features.

Programs Reviewed

Reactive Materials[1]

Findings

The concept is to develop energetic penetrating materials that exploit the synergy between the properties of the ordnance and those of the target to maximize damage to the target. The lethality of warheads is enhanced by a combination of kinetic and chemical energy released by reactive fragments when the target is hit. The cumulative effect of various damage mechanisms can increase the probability of target kill. Integrating the energetic penetrating materials in the structure of the warhead and optimizing the packaging and delivery options can also improve effectiveness.

However, current mathematical models and materials characterization do not yet allow quantitative predictions that would be useful for the design of the ordnance. Also an open question is how easily a target could be modified and protected from such optimized adaptive ordnance.

Work in reactive materials has two parts. The first includes development of more energetic explosives and the use of reactive materials as fragments to be applied explosively to the target in addition to the energy released within the target by the warhead bursting charge. The briefing indicates that projected advances are being regularly validated through experimental work, which appears to be well organized and productive. The reactive materials are of several compositions. The current baseline composition is aluminum (Al) powder suspended in a perfluoro polymer (PTFE or a similar derivative). When a conventional explosive propels a reactive fragment of Al/PTFE into a target, the fluorine in the PTFE reacts violently with the Al. As the Al/PTFE passes through the wall of a target, it reacts with oxygen in the air to produce an explosion within the target, causing much more damage.

Other energetic material compositions include thermitic material such as Al + MoO_3 with a PTFE binder. This material is also known as a metastable intermolecular composite. The fluorine serves to initiate the reactivity of the Al. There are other fuel plus oxidizer thermitic materials that can advance this technology.

The second part of the work is the development of honeycomb warhead structures into which the explosive material can be infused. While somewhat less advanced, the work appears to be sound. There are several approaches to enhancing the energy of the warhead. These include new energetic molecules, the use of finely divided (nanosize) metal powder (e.g., aluminum or hydrides such as aluminum hydride), new metastable states, and sol-gel techniques for encapsulating these materials. Nano laminate materials also offer the possibility of hard energetic cases that will withstand penetration at high velocity and contribute energy when detonated via intermetallic reactions. The work is well coupled with the national effort in energetic material—the National Energetic Material Program and the Joint DOD/DOE Office of Munitions memorandum of understanding.

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[1]As presented to the committee, this D&I thrust encapsulates Code 351's weapons-related efforts in the Missile Defense Future Naval Capability (MD FNC). The objectives of the MD FNC are as follows: (1) respond to the Joint Requirements Oversight Council (JROC)-approved Joint Theater Air and Missile Defense mission need statement and capstone requirements document and (2) demonstrate emerging and maturing technologies that span the full spectrum of theater air and missile defense. See <www.onr.navy.mil> for additional details.

Recommendations

One aspect of reactive-materials work needs some attention. Reactive fragments enhance lethality by causing a large explosion within the target. A countermeasure that might be employed would prevent the reactive fragment from penetrating the target. Thus, it is necessary to incorporate the reactive materials in robust penetrating fragments to ensure that the explosive reaction takes place within the target. Additional efforts should be undertaken to develop multifunctional missile bodies (energetic structural composites) and high-density fuels with focus on nano thermites. Modeling and simulation work should emphasize coupling reaction kinetics with mechanical energy due to impact and to improving estimates of timing and fragment design for penetration.

Thermobaric Explosives

Findings

Thermobaric explosives are a variant of a Russian composition based on cyclonite/Al/isopropylnitrate. Its virtues are that it produces a long-duration hydrostatic pressure and thermal wave inside a target such as a building or tunnel. This technology is not generally useful in achieving lethality in open areas. However in urban warfare and in the neutralization of tunnels, caves, and buried enclosed structures, the long-duration pressure and thermal pulse can significantly enhance target defeat.

Thermobaric explosives work is aimed at eventual Navy participation in an advanced concept technology demonstration (ACTD) of an improved thermobaric weapon. Time did not permit discussion of the characteristics of the candidate explosives or experimental results to date, but the developmental approach seems reasonable. A briefing chart indicates that the transition strategy is to produce 10 to 20 thermobaric weapons as warfighter deliverables to be residual assets. The committee hopes that this was an error made during chart preparation, and that the weapons will be used only as part of the ACTD. The production of 10 to 20 thermobaric weapons would serve to conduct experiments as part of the ACTD and to count also as residual assets, which are a requirement of ACTDs. If they are to be issued to warfighters, safety qualification will be necessary.

Recommendations

The initial effort of the Navy to develop thermobaric weapons was driven by the rapid response to the war in Afghanistan. The Navy now needs to conduct a reasonable R&D effort to improve the composition of a fieldable thermobaric explosive composition. Such a composition would ideally have an initial low-level explosion to disperse the fuel reactants of the composition and trigger a deflagration similar in concept to fuel air explosives. The deflagration would grow as the reactant fuels are further combusted by the oxygen in air. In addition, any combustible materials in the structure would be added to the combustion-driven shock wave inside the target.

ONR should ensure that any thermobaric weapons delivered to operational units, even for ACTD purposes, are subjected to safety review and analysis, the results of which are shared with the persons who will use the demonstration weapons. They should be issued for warfighting purposes only after the conduct of operational test and evaluation.

Survivability

Findings

Survivability work also has two parts. The first is the response of a weapon or launch platform to accidental hazards and its vulnerability to attack. The response of a munition to thermal events (e.g., fire) has been troublesome to the Navy onboard its vessels. This is commonly called the cook-off hazard. It is for this reason that the Navy is focusing on the fire problem while also conducting conventional trials against other threats such as occur when a weapon is dropped or when it is hit by enemy fragments.

To predict the violence of explosions caused by cook-off, the Navy is utilizing cook-off models. Because DOE faced this hazard with nuclear weapons, the Navy is adapting the DOE models to its needs. Cook-off model validation is needed to more confidently predict the violence of explosions caused by cook-off. The applicability of the models to newer explosives has not yet been demonstrated. This work is expected to lead eventually to confidently predicting the cook-off behavior of an actual ordnance item, but no timetable was given.

The second goal of ordnance survivability is to improve the ability of ordnance to penetrate deeply into a target without exploding prematurely owing to the shock of target entry. Work in penetration-survivable explosives aims to develop explosives that perform well in adverse thermal and shock environments so they can be used as payloads in hypersonic weapons against deeply buried targets. Early successful experiments were conducted using a very insensitive DOE explosive based on triaminotrinitrobenzene to demonstrate this capability. Further work will be necessary to develop a Navy composition suitable for large-scale manufacturing.

Recommendations

The Navy should continue to develop its capabilities to model the cook-off response of weapons. It should develop a highly interactive experimental and calculational program. This should be done in continued close collaboration with the DOE laboratories.

The Navy must develop a more tractable explosive composition for use in its penetrating munitions. This should be done in concert with the other Service laboratories under the aegis of the National Energetics Program.

DIRECTED ENERGY

Overview

The Navy has a distinguished history of research, development, and testing in the field of directed-energy weapons (DEWs) including high-energy lasers (HELs). Beginning in the 1970s with the development of the Navy pointer-tracker and the Navy chemical laser, many milestone experiments have been conducted in propagation and lethality, including full-scale tests against aircraft and missiles. The Navy HEL program essentially ceased in the mid-1990s and after a hiatus of 6 years was reestablished in FY02. The Navy also sponsored and was active in a charged-particle beam DEW program that was being considered for naval ship self-defense in the 1970s and 1980s.

An assessment of the new ONR HEL program must be tempered by the fact that it has been in existence officially for less than a year and there are no major technical results. Moreover, no real information was presented on total funding estimates or technical objectives for FY03 and beyond. Observations will be limited, therefore, to programmatic objectives for FY02 as outlined in the briefing.

To establish a perspective on the FY02 ONR-managed HEL effort, it is useful to note that the funding total of $31.8 million consists of $6 million from ONR, $9.4 million from the DOD Joint Technology Office (JTO), $2 million from NAVSEA, and $14.4 million from congressional add-ons. There are also inherent research benefits derived from the use of the DOE-funded Jefferson Laboratory, where the free electron laser (FEL) testbed is housed. While the intent of this assessment is to evaluate the use of ONR funds in HEL research, it is necessary to comment on aspects of the overall program.

The $6 million of ONR HEL funding is divided among three more or less equal efforts: FEL testbed enhancements to increase power output; propagation and lethality experiments; and mission analysis including the shipboard integration of HEL systems and CONOPS. Congressional add-on funds are also being used for lethality testing and mission analysis and for lethality tests against specific materials, such as ceramic radomes at the White Sands Missile Range (WSMR) HEL test facility. The DOD Joint Technology Office (JTO) supports laser propagation research, high-power solid-state laser development, and FEL upgrades and lethality testing. NAVSEA is supporting technology development through SBIR projects.

Program Reviewed

High-Energy Laser Efforts

Findings

As a general observation, the ONR program is well balanced among the basic elements of HEL system requirements and its funds, as well as those from outside sources, are being managed in an effective manner. The FEL testbed has been operating 24/7 for several years at a nominal 1 kW. It is currently (second and third quarters of 2002) being reconfigured for 10-kW service. No risk appears to be associated with this upgrade. When operated with additional power and higher beam currents, the configuration for 10 kW can be extended to 100-kW operation with modest risk. For 100-kW operation, the largest risk is associated with mirror cooling. Extension to 1 MW involves some risk. In order to keep the footprint of the proposed shipboard FEL to an acceptable length (the laboratory configuration extends about 30 meters in its greatest dimension) and in order to minimize the field and weight requirements of the bending magnets, the accelerator voltage has been held to about 200 MeV. If the objective is to reach 1 MW of optical power, beam current must be increased to about 600 milliamps, and space charge effects may limit operation. Current computational models show that beam currents of this magnitude may be at the upper end of feasibility. If operating levels above 1 MW are required, the necessary energy probably cannot be achieved with greater currents. Rather, the voltage must be increased. This, in turn, will increase the length dimension of the footprint of the FEL and the weight of associated wiggler and bending magnets.

Current program concepts are to build a ship-portable 100-kW machine if the 100-kW machine is successful in testbed operation. The portable unit will address the engineering problems associated with shipboard integration and will be used for propagation and lethality studies.

Preliminary designs for the portable machine will incorporate the following:

- Recovery of beam energy with a decelerator;

- Modest shielding for the weak x-rays that will result from the dumping of residual low-energy electrons after deceleration;
- An overall footprint of about 30 × 8 × 8 meters; and
- Wall-plug-to-photon efficiency of 4 percent for the 100-kW machine and 8 percent for the 1-MW machine. (The efficiency of the current 1-kW machine is 0.5 percent.)

Recommendations

For reasons of propagation, 1 micron has been selected as the preferred laser operating wavelength. However, the presence of such an HEL in the fleet at sea and in littoral environments presents a danger to the eye that would require compensating changes in Navy operating procedures. Moreover, use of this unsafe wavelength might violate existing treaties to which the United States is a signatory. The optical absorption curve in the vicinity of 1.0 micron is very steep. Optical transmission through the maritime atmosphere might fall by a factor of between 10 and 100 as one moves the laser's operating wavelength from 1.0 micron to, say, 1.2 microns. While there may be a reasonable level of confidence that a 1-MW FEL compatible with shipboard operation can be built, there is at present no reason to think that an extrapolation to a shipboard 10-or 100-MW FEL is feasible.

A detailed systems study of these implications should be conducted, including the trade-offs of alternative laser operating wavelengths, as needed.

The Navy pioneered pointing and tracking experiments in the 1970s for fleet defense against air and missile targets. As noted in the ONR briefings, the new target set is diverse and includes asymmetric threats such as terrorists on jet skis. The ONR program should include the pointing and tracking problem associated with targets that must be acquired in sea clutter such as small boats or jet skis. The program should demonstrate that the Navy has the ability to detect, identify, and point the laser at these proposed new targets at very low elevations.

The attempted development of high-power solid-state lasers has a long and checkered history. Other than a brief discussion in the read-ahead materials provided to the committee, the state of the art in this area and the competing approaches were never mentioned. ONR should prepare a summary to compare competing techniques with their choices.

A significant ongoing effort in solid-state laser is being conducted at the Lawrence Livermore National Laboratory under Army sponsorship. It is called the heat-capacity solid-state laser (HCSSL) since the lasing material is allowed to rise in temperature while still functioning and then allowed to cool. It has achieved approximately 12 kW. The program in place will develop a 100-kW demonstration solid-state laser that will be mountable on a small vehicle such as a high-mobility multipurpose vehicle (HMMV).

Propagation of laser radiation also has a long history of theoretical and experimental study. ONR should provide a historical record that explains why the current approach of laboratory simulation is being pursued and what it will add to the existing body of propagation knowledge.

The Navy should also consider the inclusion of high-power microwave weapons in its ship self-defense portfolio, particularly for close-in asymmetric threats. This would include the vehicle mounted active denial system developed by the Air Force Research Laboratory for the Marine Corps. This might provide a powerful nonlethal disincentive to any terrorist approaching a ship. A more powerful variant of this could enhance ship self-defense by neutralizing any attacking weapons.

GUN WEAPONRY

Overview

In 1999, a cost operational effectiveness analysis (COEA) supported the use of naval guns for naval surface fire support. Specifically, the analysis concluded that a 155-mm advanced gun concept was the most cost effective of the options considered. The Navy adopted the COEA recommendation with the caveat that its interim capability be maintained by incremental upgrades of the 5-in. gun firing a rocket-assisted extended-range guided munition (ERGM). The 5-in. upgrades met the total range requirement of 41 nmi (minimum threshold) to 63 nmi (stated objective) established by Operational Maneuver From the Sea (OMFTS) battle philosophy. The COEA used Navy-approved scenarios and target sets at distances greater than 63 nmi. The 155-mm gun with a scaled-up version of ERGM proposes to extend the range to 100 nmi, thereby encompassing a higher percentage of the target set.

The generic problems facing the use of guns in the mission of fire support are the following:

- Targeting of fixed, relocatable, and moving targets,
- Target recognition,
- Total response time for delivery of weapons to the target,
- Warhead lethality,
- Weapon range,
- Weapon guidance, and
- Rate of fire.

The ONR programs in this and other thrust areas address most of these problems. In gun technology, the main thrust areas are these:

- Projectiles (including warheads, fuzes, aeroshells),
- Guidance for projectiles,
- Propulsion for rocket-assisted projectiles, and
- Launchers, internal ballistics, and gun propulsion.

Much of the technology in these areas can be synergistically applied also to missiles. In general, the committee found the programs in this area to be useful, in particular for application to the 155-mm gun/projectile system. Indeed, as has been mentioned, much of the work is directly applicable to present and future missiles. However the committee believes, as discussed in the recommendations of Chapter 2, that the Navy is approaching the range limit with gun systems and that any further requirements for increased range would be better served by missile systems. Pushing rocket-assisted gun-launched projectiles for more range than that demonstrated introduces new problems: hotter propellants, gun barrel erosion, and more severe in-tube environments. While there is no current Navy requirement for ranges longer than 100 nmi, there is discussion of ranges of 200 to 400 nmi, to match the Osprey range. (It has been noted that the Marine Corps needs rockets or missiles, not guns, for long-range fire support.) The presentation further alluded to the use of light gas guns and rail guns. The committee notes that the Army is doing engineering designs on an electrothermal chemical gun for its Future Combat Vehicle that has a higher muzzle velocity than a powder gun and reduces the vulnerability of magazines since it requires no conventional gun powder. Rather, it uses onboard electrical energy to convert an inert material such as polyethylene into a plasma to propel a projectile.

An electromechanical gun may also have promise, but it requires a tremendous amount of electrical energy and volume for compulsators and similar electrical pulse generators. There is also concern over the lifetime of the launch rails.

The committee cautions ONR that system studies should be performed before any funding is given for experimental studies and that these long ranges should be handled with missiles. Specific findings and recommendations for each of the thrust areas are provided below.

Programs Reviewed

Projectiles

Findings

ONR has technology programs addressing the following:

- Increased warhead lethality by using mission-responsive ordnance, kinetic-energy projectiles, advanced energetics with reactive warhead materials, and higher-yield explosives.
- Higher-performance projectiles by improving the aerodynamic drag characteristics of the projectile. This program culminated in the barrage round, which was a ballistic conical round that achieved a range of 43 nmi in 3 minutes time of flight after launch from a 5-in. gun. This work has apparently been terminated for reasons not made clear.

ONR programs in this area have provided useful analysis tools for aerodynamic predictions of range for various low-drag shapes and for warhead lethality predictions.

Recommendations

The committee endorses the work being performed or already completed in the projectile area.

Guidance for Projectiles

Findings

A number of ONR-funded programs in this area have provided big payoffs, which have transitioned into Navy acquisition programs. These include MEMS, Global Positioning System (GPS) receivers, and tightly coupled guidance systems. Future thrusts after FY04 are programs in three areas:

- High-acceleration load guidance and control systems,
- GPS antijam and/or non-GPS guidance systems, and
- Infrared and millimeter-wave seekers.

The payoff of guidance improvements is manifold since they are applicable to missiles, decrease the number of rounds required to kill a target, and ease other problems, such as logistics support.

The committee is impressed with the success of previous ONR investigations into low-cost, high-accuracy guidance systems.

Launchers, Internal Ballistics, and Gun Propulsion

Findings

ONR has funded programs in this area aimed at improving the propellants for rocket-assisted projectiles. These have resulted in propellants with high Isp operating at higher pressures than conventional rocket motors. The main efforts in this area are concerned with achieving higher-performance propellants and minimizing the barrel erosion that is associated with these hotter propellants. Most of the work that was presented to the panel dealt with the gun erosion problem. The committee believes that there should be a better way of identifying new barrel coatings to minimize erosion than the cut-and-try method that is presently being followed. On the other hand, the committee found the composite material barrel concept interesting and suggests that it should be continued. The schedule by which the work is to be advanced appears not to allow sufficient time for model validation and application.

Recommendations

The committee believes that range performance beyond the 60 or so miles already demonstrated should not be sought for this technology. The longer range fire missions are probably better handled by solid-rocket-propelled ballistic missiles. The attendant barrel erosion problems lead to the need for barrel liners, and high setback acceleration requirements and the logistic issues associated with a gun round that is large (and requires a double tamp loading) are problematic. While interesting to work on, in the committee's view these problems are barriers to the effective use of guns in the longer range fire support role.

PRECISION TARGETING AND GUIDANCE

Overview

The principal science-and-technology objective of this thrust is to develop the targeting and engagement technology base required to support naval combat through improved responsiveness, precision, and dependability against targets that are time-sensitive, that are stationary or moving, that are in urban or close-support settings, and that can be soft or hard. This technology should also improve the performance of tactical airborne and shipboard fire-control systems. Products of this thrust are applicable to current and future weaponry that may be operated manually, automatically, or autonomously. These products should support hit-to-kill weapons, provide positive target identification with greater than 90 percent acquisition probability, minimize the likelihood of collateral damage or vulnerability of the weapon launch platform, and be capable of operating at any time of day and in a wide range of operational environments. Phases of operation include search, detection, acquisition, track, classification, identification, target and aim-point selection, raid count, commit-to-fire, prelaunch, postlaunch, midcourse, terminal intercept, and damage assessment. The committee notes that its observations regarding scene correlation and fusion discussed in reviewing the TCS image video analysis thrust apply here as well.

While there is growth in the total Code 351 budget for FY00-FY03 (see Table 1.1), the breakdowns reflect a movement away from discretionary spending and D&I toward externally mandated programs and FNCs. Furthermore, there is a complete lack of 6.1 funding in this area. It is noted that related ONR and non-ONR programs may contribute to the goals of this Code 351 thrust and are not the subject of this review. The committee applauds increased efforts to transition the fruits of scientific and technological research to the operational Navy, where the direct payoff lies. Nevertheless, it is concerned that increased emphasis on short-term goals will materially detract from Code 351's ability to explore innovative concepts that ultimately could provide even greater benefits for naval operations.

There are many examples of fundamental research areas that could have considerable impact on responsive targeting and precision guidance, but they were not briefed to the committee. These include multispectral sensing methods, incorporation of contextual information in target detection and identification, advanced state estimation, supervised and unsupervised neural networks, optimal stochastic approximation, rule-based techniques for decision making, and human-machine interactions and interfaces. The committee notes, for example, that the holy grail of automatic target recognition under harsh, deceptive, and dynamic environments remains as far in the future as ever under the current Code 351 program. Even if these cutting-edge technologies are being addressed elsewhere, their omission from the Code 351 agenda slows the pace with which they could be introduced to related FNC processes.

The read-ahead package for this thrust provides a good technical summary of 12 subthrusts. In the remainder of this section of the report, the committee addresses the three subtasks that were presented to the committee. The committee notes that there is commonality among the technologies if not the direct goals of the three subtasks. ONR can play a critical role in assuring that there is beneficial communication and collaboration among these projects. The committee was not briefed about related on-going programs within the sister Services. Because these topics are of such broad significance and research efforts are costly, it is important that the ONR coordinate its programs with those funded by the Air Force Office of Scientific Research (AFOSR), the Army Research Office (ARO), DARPA, and individual DOD laboratories.

Programs Reviewed

Imagery-Enabled Strike Targeting and Weapon Guidance

Findings

This subtask is further subdivided into three parts: (1) precision target handoff (PTHO; 6.2), (2) direct attack munition advanced seeker kit (DAMASK; 6.3), and (3) digital precision strike suite (DPSS; 6.3). The PTHO program, completed in FY01, developed techniques for real-time location of targets (within 5 m) from tactical sensor images, and incorporation of national imagery and data from tactical sensors, decreasing the reliance on GPS. The DAMASK program, also completed by FY01, demonstrated laser-guided-bomb delivery accuracy (less than 3 m) using commercial off-the-shelf (COTS) technology and image-based guidance with and without GPS. The DPSS program was begun in 1998 and is scheduled to enable the fielding of an operational system in FY06. It will allow a pilot to designate a target of opportunity from real-time imagery (e.g., forward-looking infrared (FLIR) or synthetic aperture radar (SAR) data), will convert the location of a static target to World Geodetic System (WGS)-84 coordinates, will cue weapon release, and will register seeker video with a template for improved accuracy.

Recommendations

The DPSS program appears to be well motivated and to have a good likelihood of success; therefore, the committee recommends that funding be provided to continue the program. The committee notes, however, that funds for continued research and exploratory development of methods for operation in more challenging environments (e.g., desertlike areas that have few features for image registration) are not programmed. Furthermore, additional research should be conducted on ways to reduce false alarm rates, to improve target identification, and to handle moving targets. It recommends additional D&I funding in this area.

Standoff Weapon Automatic Target Recognition

Findings

The critical issues for automatic target recognition (ATR) are adaptation to dynamic mission conditions, predictability of ATR performance, and automatic recognition of mobile targets (both moving and static but relocatable on short notice). Target sensing may benefit from the use of laser radar (LADAR), which can provide three-dimensional information and can extend the range at which targets can be identified. LADAR offers the possibility of achieving better target resolution in angle and in range. At low grazing angles, a LADAR can locate the target more precisely by measuring the true range rather than projecting back to ground level using an assumed target height. One possible application of such systems is in a submunition-dispensing variant of the Tomahawk cruise missile.

Reliable adaptation to dynamic mission conditions enables real-time retargeting of a cruise missile, including strike on multiple targets. Seeker and system development has started, with flight demonstrations to begin in FY03. There remains the issue of deciding whether or not to accept and act upon the information provided by ATR. Here, it is critical that a good upper bound be placed on target location error, for if the error is too large, the risks of collateral damage and unnecessary expenditure of a weapon are too high to allow deployment. Image processing for ATR is computationally intensive by any measure, and existing equipment does not allow current methods to be executed in real time. The problem is exacerbated by moving targets, natural features and cover, deceptive actions of the enemy, and discriminating of military targets from civilian resources. Results to date are impressive from a narrow technical viewpoint, but there is much work to be done before implementation could be considered. At a minimum, the complicating factors noted above must be taken into account.

Recommendations

Code 351 should provide to those working in this area added guidance on broader goals and the likely pathways to achieving operational ATR, challenging important 6.1 and 6.2 enabling technologies. In particular, the committee recommends that much greater effort be directed at the 6.1 and 6.2 levels, toward solving the complicating problems of ATR, most particularly integration of data from possibly disparate sources and automated intelligent decision-making with this information.

Precise Tactical Targeting

Findings

The goal of this subtask is to develop a systematic approach for using a standoff platform to provide affordable, near-real-time target information for GPS-guided weapons, with initial operational capability of 10-m accuracy in 2007 and demonstration of 1-m accuracy in 2010. The approach uses distant GPS control station data for improved platform location accuracy, low-cost inertial measurement of platform position and attitude, COTS digital electro-optical cameras for imaging the target and its surroundings, triangulation and/or laser ranging for target positioning, and advanced estimation algorithms. It also uses imagery and terrain models from other sources to register the standoff observations. The targeting problem is made difficult by the obliquity of the target viewing angle, intervening terrain, seasonal variations, new construction and ground clearing, battle damage, cloud cover, and lighting. The project is well described, and it reflects a logical progression toward a worthwhile goal.

Recommendations

The committee recommends that the precise tactical targeting program be continued and that it be augmented by appropriate 6.1 funding, which also may benefit the previously reviewed programs.

PROPULSION AND AEROMECHANICS

Overview

The ONR work in Code 351 dealing with Propulsion and Aeromechanics that was briefed to the committee appears primarily under two headings: (1) hypersonic weapons and (2) integrated high-payoff rocket propulsion technology (IHPRPT). However some aspects of propulsion and aeromechanics also appeared in several other briefings, including those on adaptive ordnance, mission response ordnance, precision strike navigator, high-speed antiradiation demonstration, and gun barrel erosion (and fatigue). Here the committee deals primarily with the first two topics, hypersonic weapons and IHPRPT, but it also touches briefly on the others elsewhere in this report in the appropriate sections.

A general observation is that the success and risks associated with these topics are significantly dependent on our ability to create and understand at a fundamental level the behavior and response of structures and materials in very hostile high-temperature, high-speed flow environments. It is not clear that the several efforts have taken full advantage of the possible interactions with the basic and applied research community in structural mechanics and materials. Thus to the extent that this is true, the committee encourages closer interaction with the basic research community and suggests the consideration of an expanded discovery and invention activity in the aeromechanics of complex systems and the development of new and improved materials.

Programs Reviewed

Hypersonic Weapons Technology

Findings

This thrust is to develop a high-speed strike capability through a hypersonic weapon vehicle. There is good partnering with DARPA and others and a thoughtful, well-planned research and development effort culminating in a flight demonstration. However, a rich array of technology challenges and opportunities remain. These range from the development of an inlet isolator and nozzle to subsonic and supersonic combustors. From the briefing it is not clear how these are integrated into the D&I process, including not only the ONR program, but also AFOSR, ARO, and so on. In particular, the structural integrity of major system components might benefit from an enhanced activity in the D&I portfolio of ONR.

HyFly Program. The hypersonic strike weapons system concept involves the development of a hypersonic air-breathing cruise missile capable of sustained mach 6.0 cruising at 90,000 ft with 4,400 ft/sec average velocity, a 600-nmi range and submunition deployment capabilities. The critical issues addressed are guidance and control, airframe, ordnance, and propulsion. Propulsion challenges are high specific impulse for long range, high thrust for high acceleration, continuous thrust for maneuverability, and throttleability. The propulsion approach involves the development of a dual-combustion ramjet engine concept. The coating of a hafnium-carbide-coated combustor section tested at Mach 6 had started to flake away, even though the woven carbon filament was intact. The mid-body is being made of cast titanium. The technical challenges facing structures and materials are mainly due to mission requirements that cause high thermal, mechanical, and acoustic loads and the fabrication of complex shapes undergoing gradients of stress and temperature. The current choices for materials are Inconel nose cone, C-SiC inlet, coated C-C or C-SiC combustor, aerogel insulation materials, and a titanium airframe.

Key Technologies in the Hypersonic Weapons Technology Program. The airframe technology area—i.e., airframe components and heat transfer technology—is progressing in a timely fashion, with careful consideration of metrics such as survivability, weight, and affordability. Designing with passive cooling requires a superior thermal protection system (TPS). Several candidates have been considered for TPS, with the RX-2390 having been chosen. Newly emerging high-temperature resin systems have been studied for the airframe skin (IM7/PT30). Multifunctional ordnance items have been looked at, that can survive high impact and thermal shocks, that are lethal, and that have a dual-mode capability (surface reaction and penetration). The guidance and control technology area is addressing mechanical survivability, electronic properties at temperature, and thermal protection. The goals are to have GPS track through reentry and hypersonic RF seekers. The propulsion technology area focuses on the dual-combustion ramjet with enhanced mixing.

The emergent ideas are passive reradiation cooling, enhanced mixing, and unconventional control by replacing control fins with low-mass reaction jets.

Recommendations

Consideration should be given to a closer synergy with and enhanced effort in basic research into structural integrity that could be relevant to this activity in hypersonic weapons.

Because one of the key issues in converting this technology into viable weapons will be the cost per round, producibility and material costs should be considered early, when making decisions on concept design.

Integrated High-Payoff Rocket Propulsion Technology

Findings

This effort is directed at achieving a substantial increase in the specific impulse of rocket engines through operation at higher pressures. It is a key part of a national program that is jointly sponsored by DOD, NASA, and industry. The goals include a significant increase in rocket propulsion capability by 2010 by increasing weapon kinematics, decreasing weapon size, and decreasing the number of weapon systems. The roadmap includes an air-launch demonstration, an advanced air-to-air rocket technology demonstration, a surface launch propulsion demonstration, and a gun-launched rocket demonstration.

The critical technologies and technical challenges include these: high-burn-rate, reduced-smoke propellants; highly loaded grain designs with adequate thrust, high-pressure, stable motor operation; high pressure, strength, and stiffness of composite cases; and low-erosion nozzle materials. The high burn rate and reduced smoke challenge is being addressed with modified end burner grain designs. The high-pressure requirement due to smaller nozzle throat in turn necessitates propellants that operate at high pressure, and there is also need for erosion-resistant nozzle materials. Even with nozzle materials like rhenium, erosion is substantial at 4,000 psi. For the propellant management devices, composite cases with high-temperature resins and high-strength fibers to allow for the high-pressure operation are being considered. In a nutshell, operation at higher pressures is leading to excessive erosion and even failure of the nozzle structure. Fortunately, and very recently, one might even say "magically," a technology has been developed that eliminates erosion and ensures structural integrity—the integrated omnivector cone (INOVEC) phase II demonstrator. The details of this technology were not shared with the committee.

Overall this program represents an impressive achievement. However to more fully evaluate the significance of the achievement in realizing improved propulsion performance and its implications for ONR R&D investment, the technology for solving the erosion and structural integrity issues would have to be known.

Recommendations

Because of the very demanding properties of the materials being considered for high-temperature and high-pressure applications, the committee recommends that the materials' producibility and overall cost per round be carefully considered in the trade-offs for design solutions. Also, the committee encourages the ONR to attempt to trace back the investments that were made that led to the development of the technology that has resolved the high-pressure erosion and structural failure issues, to determine if this is an example where the ONR D&I process has made a significant contribution to an FNC.

4

Thrusts of the Time Critical Strike FNC Program

OVERVIEW

Time-critical strike is certainly one of the most important components of modern warfare and accordingly warrants a significant investment of ONR's resources. The importance of time-critical strike is also reflected in the significant S&T investments in this area by the Air Force and by the Defense Advanced Research Projects Agency (DARPA). Some components of the Time Critical Strike Future Naval Capability (TCS FNC) program appear to be coordinated closely with parallel DARPA and Air Force programs. Other components represent efforts that are unique to naval requirements.

The integrated product team that provides guidance for the TCS FNC has identified many capability gaps and the enabling capabilities needed to defeat five classes of targets:

- Expeditionary warfare targets with naval fires;
- Relocatable targets at range;
- Short-dwell mobile targets at range;
- Moving targets at range; and
- Active hard and deeply buried targets at range.

Because of resource limitations, the TCS FNC is not scoped to try to eliminate all of the gaps in the capabilities needed to defeat the five classes of targets.

Many factors determine success in time-critical strike. In the sense that it is used in that term, "time" is the sum of the times needed for the following:

- For identifying and geolocating a valid target;
- For deciding to attack the target; and
- For a weapon to travel from its launch point to its intended target.

The word "critical" refers to the fact that the sum of the times listed above must be less than the total time that a mobile or relocatable target remains where it was projected to be located at the time of weapon launch. Thus, if the military leadership of an adversary is determined to be in a specific building, that building will be a critical target only as long as the group of interest remains within the targeted building. In the event that the target is in continuous motion, the time-critical strike problem converges to the moving-target problem.

The word "strike" in this context refers to the capability of delivering a weapon of sufficient accuracy and lethality to destroy the target while it is still a valid target.

Traditionally there have been two approaches to the time-critical strike problem. One has been to reduce the times needed to identify, geolocate, and decide to attack targets. When the target sensor and the weapon are on the same platform (as, for example, on a manned strike aircraft), the problem is somewhat less complex. If a pilot locates a target with onboard sensors or with the aid of a ground observer, and if the pilot's rules of engagement are satisfied, a weapon can be released. In such situations, the time-critical strike problem is simplified.

A more difficult situation occurs when the sensor that detects the target is not colocated with the weapon release platform. In that case the decision-making process can be long compared with the dwell time of the time-critical strike target, and the time of flight of the weapon can be significant.

The second approach is to reduce the weapon's time of flight to the target once it has been launched. There are two traditional ways to reduce weapon time of flight: (1) produce a weapon system (rockets or hypersonic weapons) that travels long distances at extremely high speeds and (2) develop loitering weapon delivery systems (uninhabited air vehicle (UAV)-borne or with sustained cruise capability) that can remain near a suspected critical target area for extended periods of time and attack the target from short ranges when commanded to do so.

Given the ensemble of future military situations that may confront our forces, both approaches are important and should, to the extent permitted by budget constraints, be included in a TCS FNC program.

The TCS FNC is comprised of eight separate thrusts, all of which relate to some individual aspect of the complex time-critical strike problem. Depending on the specifics of an individual conflict, the significance of these thrusts may vary from being highly significant to marginal. The TCS FNC thrusts are as follows:

- Cruise missile real-time retargeting;
- Image and video analysis;
- Enhanced target acquisition and location system;
- Precision strike navigation;
- Mission-responsive ordnance;
- High-speed antiradiation demonstration;
- Weapons imagery link; and
- Gun barrel erosion (and fatigue).

Pursuant to the constraints of the FNC process and its budget, no attempt is made within the TCS FNC to find more global solutions to the overall problem of engaging time-critical targets by naval forces. Instead, the effort addresses about seven specific limitations of current systems.

Among the longer components of the total time required for the time-critical strike process is the time required to locate and identify valid military targets with sufficient certainty to allow a military commander to authorize the release of a weapon to that target. The image and video analysis thrust addresses the problem of reducing the time required for target identification using electro-optical imagery produced by specific sensors such as the F/A-18 SHARP electro-optical system and/or by the synthetic aperture radar (SAR) imaging sensor on the Global Hawk and/or the Predator.

No other thrust is being supported under the TCS FNC that will result in sensors that allow more rapid and efficient target detection in difficult environments or sensors that will better discriminate between military and civilian targets or between military targets and decoys.

The cruise missile real-time retargeting and mission-responsive ordnance thrusts may be interpreted as a limited approach to the development of a loitering weapon capability that would allow the rapid engagement of critical targets once they have been detected and authorized for attack. The main limitation of this approach is that the loiter time of a cruise missile such as the Tomahawk is probably limited to about an hour at most. Thus, these thrusts represent an important but fragmentary approach to development of the overall capabilities needed for successful true loitering weapons.

In summary, unless the thrusts that are contained in the TCS FNC currently under way are rejected by the intended transition recipient, it is recommended that they should be pursued to completion. Looking to the future, the committee recommends that the current thrusts should be replaced by a more meaningful program that reflects Joint (Navy and Air Force) priorities for TCS such as in Chapter 2, “Responding to Operational Requirements” and “Recommended New Program Areas.”

The committee’s assessment of the eight thrust areas that make up the TCS FNC are provided in the next section.

PROGRAMS REVIEWED

Thrust 1: Cruise Missile Real-Time Retargeting

Overview

The objective of this program is to produce a capability that employs Tomahawk cruise missiles (submunition variants) against time-critical targets by leveraging LADAR seeker technology from the low-cost autonomous attack system weapon system.

The evolving CONOPS assumes that a Tomahawk missile is launched against a primary target or makes a brief excursion to attack a new target and, in the future, will be placed into loiter. If a time-critical target were detected while the missile is in flight or in loiter position, target data would be sent to a strike cell coordinator, who would overlay the target data on a georegistered database. The Tomahawk would then be retargeted while in flight or in its loiter position. Two minutes before reaching the main target area, the missile would receive target update data. The Tomahawk’s LADAR seeker would then be used to locate and identify the targets and to activate the Tomahawk’s submunition dispenser. If the target is killed or hides prior to attack, the Tomahawk would be placed back in loiter (subject to fuel constraints).

The key technical challenges identified in the development of this CONOPS are the following:

- Form, fit, and function for an eye-safe tactical Tomahawk seeker,
- Compact size,
- Low power,
- Thermal management,
- 200 *g* shock hardening,
- Low cost,
- Timely ATR processing of dense target areas, and
- Predictable and reliable performance of ATR, sensor manager, and search algorithm under conditions of target obscuration, confusers, and moderate clutter.

The technology demonstration program is divided into four build phases, with planned completion in FY05.

Findings

This thrust is proceeding in a well-organized manner with well-defined objectives and milestones. The perception of the committee is that the greatest area of risk relates to use of an automatic target recognition (ATR) algorithm that will be used to control the dispersal of submunitions. The committee is confident that the ATR algorithm will work well in situations where few confusing targets exist and where the probability of causing collateral damage is low. Unfortunately, there are many situations that do not meet these criteria or where the rules of engagement demand very high confidence that the ATR algorithm will not permit attacks on unintended targets.

If total dependence on an ATR algorithm proves, in some situations, to be unacceptable to a local commander, alternative capabilities—e.g., the data link being developed under the weapons imagery link (WIL) thrust—should be explored for incorporation into this excellent weapon concept. WIL would allow the inclusion of man-in-the-loop capabilities to cover situations where the use of an ATR algorithm might not provide enough confidence in the ability to avoid collateral damage and satisfy rules of engagement constraints.

Recommendations

This program should be pursued as scheduled. More effort should be devoted to verifying the ATR algorithm that is selected for inclusion in the weapon. Provision should be made for eventually including the product of the WIL thrust if it is successful.

Thrust 2: Image and Video Analysis

Overview

The objective of this program is to accelerate the exploitation of tactical imagery to improve targeting and battle damage indication capabilities against real-time-critical mobile targets. Sources of tactical imagery currently being addressed are the infrared/electro-optical sensor in the shared advanced reconnaissance pod (SHARP) carried by the F/A-18 aircraft and on the Global Hawk UAV SAR.

The stated goals of the image and video analysis (IVA) thrust are as follows:

- Focus of attention subsystem (FOAS): provides automatic detection of relocatable targets in SHARP imagery;
- Automatic imagery registration subsystem (AIRS): automatic registration of tactical imagery to digital point position database (DPPDB);
- Automatic battle damage indication: automatic detection of indications of battle damage in SAR imagery; and
- Image compression: automatic compression of tactical imagery while maintaining target information.

The IVA program is envisioned to provide integrated software capabilities that can be transitioned to the Joint Services Imagery Processing System-Navy (JSIPS-N) image exploitation system via software modifications to the Tactical Imagery System and to the Precision Targeting WorkStation in the 2006-2007 time frame.

Findings

The limitation of the FOAS of IVA is that available systems address only nonobscured targets when there is light clutter in the vicinity of the target. The goal is to develop new techniques that will achieve an 80 percent probability of detection with a false alarm rate of 0.01 per frame. The idea is to partition images into regions of uniform clutter and provide overlays that will process out the clutter in each such region. Known false targets will be eliminated on a detection map, and recent changes will be noted. The FOAS is designed to reduce the burden of work on a human image analyst.

The objective of AIRS development is to achieve automatic registration of tactical imagery against national and digital point position databases. The goal is to achieve tie-point registration through a least-squares adjustment to referenced tie points.

Work on battle damage detection and on image compression will not start until fiscal year 2005.

The anticipated payoff of the IVA thrust is to improve the performance of JSIPS-N targeting for TCS against relocatable targets through the use of aided man-in-the loop image exploitation. The sense of the committee was that this problem was being approached somewhat in isolation and that it addressed only part of the chain. As was pointed out by the briefers, the problem has several parts, which can be described as follows. First is the correlation and fusion of area scenes from different sensors with different viewing angles, distances, different optical and RF spectrums, different resolution, and different display media. Second is the discrimination of potential objects of interest from normal terrain and vegetation, especially when camouflaged, based on unique signatures. Third is placing those objects in the context of the area to determine combat identification for a strike decision and, fourth, providing the strike mission plan and the data necessary for the shooter to approach, properly designate, and engage the target with the SHARP system as primary onboard sensor.

Three observations are offered. First, multispectral sensing of the same scene is key to the target recognition and false alarm problem and should be exploited in the solutions being pursued. Second, high-speed, scene-to-scene correlation can often be best implemented using special-purpose, array-processing hardware and software. Third, the translation of one sensor platform's scene view to another sensor platform's view of the same area and their correlation and fusion and, later, the generation of a weapon lay down and shooter view can make use of modern commercially available terrain-rendering engines. These engines must be supplied with the GPS/inertial navigation information on each sensor platform and with the digital, theater-specific terrain databases that must be developed prior to theater entry. This process generates a rapidly adjustable "God's-eye" viewpoint to create common views by all sensors that can then be correlated. The committee noted that some excellent related work going on in the responsive targeting and precision guidance D&I thrust may help in the specific SHARP application being addressed here.

Recommendations

This effort should be pursued to completion following the present schedule. The work on battle damage detection should be accelerated. The USAF and the National Reconnaissance Office are sponsoring related efforts. Coordination with these related efforts should be established if it does not already exist.

Thrust 3: Enhanced Target Acquisition and Location System

Overview

The objective of this program is to improve target location accuracy and timeliness for the remote targeting systems used by Marine Corps forward observers and forward air controllers. The main source of setup time latency and target location inaccuracy is the current magnetic sensor used to provide target-bearing measurements. The enhanced target acquisition and location system (ETALS) will replace the magnetic sensor with a gyrocompass that has the following characteristics:

- Calibration time under 2 minutes;
- Azimuth accuracy to about 0.5 degrees (4.36 milliradians (mils);
- Weight under 2 lb; and
- Cost less than $7,500 in quantity.

A secondary ETALS objective is to provide the capability for using the advanced eye-safe range-finder observation set (AEROS) to communicate digitally with the target handoff sensor, thus creating a seamless, low-cost daytime targeting system.

The target location error (TLE) of the present operational system is driven primarily by the azimuth error, which provides a circular error probable (CEP) of 50 m at a range of 5 km. Improving the azimuth error to less than 5 mils will have diminishing returns, as current GPS position errors become the dominant error source. Unless differential GPS is employed, a 0 mil error azimuth determination system would have a TLE of 8.6 m regardless of range.

Finding

ETALS is progressing well toward transition to Program Manager Ground Weapons.

Recommendation

Continue the present program to transition.

Thrust 4: Precision Strike Navigator

Overview

Missiles are normally guided to their intended target by an inertial measurement unit (IMU). The reference gyroscopes in the IMU drift. In an unjammed environment, GPS measurements are used to correct for the drift of the gyroscopes and ensure that the weapon is guided to its intended target. When GPS signals are jammed and the IMU drift cannot be removed, the weapon will miss its intended point of impact.

For relatively short time-of-flight (TOF) weapons such as the joint direct-attack munition (JDAM) a low-drift-rate gyro will reduce or eliminate the need for a GPS update to offset gyroscopic drift. Thus a short TOF weapon with a low-drift-rate gyroscope would be immune to the effects of GPS jamming.

Low-drift-rate gyroscopes are available, but their current costs are large compared to the cost of a weapon such as JDAM. A low-cost, low-drift-rate gyroscope would greatly improve the performance of guided weapons that are potentially vulnerable to GPS jamming.

The objective of this program is to demonstrate a high-level hybridization in the electro-optics of a low-cost fiber-optic gyro. The hybridization will allow for high accuracy IMU performance in a jamming environment at a price appropriate for tactical weapons.

Specific program goals are as follows:

- Gyro bias stability of better than 0.02 degrees per hour,
- Projected unit production cost of $6,000 for a three-axis IMU, and
- Achievement of glide weapon CEP objective without the help of GPS.

Findings

If the goals of this program are achieved, the performance of short TOF weapons in the presence of GPS jamming will be made robust at an affordable cost.

The initial prototypes produced under this thrust achieved the desired performance (less than 0.02 degree/hr). Unfortunately, they were not amenable to low-cost, high-rate production. Work is continuing on a design that can be produced at high rates of production and low cost.

Recommendation

Given the military importance of this program, this thrust should be pursued to a successful completion.

Thrust 5: Mission Responsive Ordnance

Overview

The objective of the mission responsive ordnance (MRO) program is to develop and demonstrate ordnance technologies that will enable a single cruise missile payload to defeat unitary, area, and dispersed land targets. Implementation is planned in conjunction with the retargetable tactical Tomahawk (TT) cruise missile.

The MRO payload is an integrated payload assembly constructed of multiple, guided, dispensable payloads termed kill vehicles (KVs). These KVs are distributed around an explosive-loaded integral charge (IC). The IC is packaged within the structure of the payload, providing the missile with a warhead when all KVs have been dispensed. The KVs are free-falling, fragmenting warheads, which are controlled by an independent guidance, navigation, and control system; thus they can be independently targeted through the two-way data link available on the TT. The IC that remains after the KVs have been dispensed is designed to be used against a default hard target.

Findings

As presented to the committee, work on the MRO thrust appears to have been initiated in the current fiscal year (FY02). The technology transfer plan was signed on April 2, 2002. Efforts to date seem to have been limited to planning and preliminary tests of warheads and KV dispenser concepts.

Many concepts have been suggested for submunitions to be carried and dispersed by large cruise missiles such as the TT. The area-attack version of the Tomahawk land-attack missile dispenses BLU-97 submunitions. These are effective against soft targets such as parked aircraft, vehicles, radar vans, and troops in the open. Other concepts postulate the use of multiple brilliant antitank (BAT) weapons.

No evidence of analysis was presented to support the view that the payload being designed for inclusion in the TT was somehow optimized for many missions or that it offered more flexibility and tactical utility than other submunition concepts. Subject to the constraints of the volume and weight available within the cargo (warhead) section of the TT, many submunition configurations are possible. For example, submunitions to attack wide-area soft targets such as truck convoys, enemy air defense, and personnel could significantly enhance their lethality with a very capable miniaturized proximity fuze for each submunition. (The committee understands that some work is going on in this area by China Lake (California) under Naval Air Systems Command sponsorship.) This thrust is in its early stages. Even if further analytic effort shows that other submunition configurations are more advantageous than the one being considered, the technology being developed is important. As an example, the committee was impressed with the concept of submunition distribution in which the submunition initially penerates the missile wall.

Recommendation

Although the TT has only limited loiter capability, the committee regards its development with efficient submunitions as an important component of the TCS FNC and recommends that it be supported strongly.

Thrust 6: High-Speed Antiradiation Demonstration

Overview

The basic antiradiation missile in current use by the Navy and Air Force is the AGM-88E. Although an excellent and effective missile, it does not incorporate new technology that has been developed since its introduction into service. In the high-speed antiradiation demonstration (HSAD) thrust supported under ONR's TCS FNC, an attempt will be made to demonstrate an improved booster that will incorporate the following:

- Nozzleless booster,
- Variable-flow ducted rocket,
- Tail-controlled steering, and
- Tail and throttle controlled autopilot.

If the HASD is successful it will be incorporated into the design of the new high-speed antiradiation missile (HSARM), which will replace the AGM-88. The HSARM will provide increased standoff range, time-critical response, increased probability of target kill as a result of increased antiradiation homing accuracy, and increased terminal seeker accuracy. Because of its increased speed, range, and low-observable propulsion and steering (relative to the AGM-88E), the HSARM should be more effective than the AGM-88E for the mission of destruction of enemy air defense. The AGM-88 is largely used for suppression of enemy air defense.

Findings

Although the objectives of this thrust are highly laudable, the technical challenges are daunting. Among them is the need to develop an integral rocket ramjet booster with no ejecta that will deliver a specific impulse greater than 200 sec along with a ducted rocket ramjet that can deliver a ramjet Isp greater than 850 sec. In addition, program success will require the development of a throttle valve with extended housing and plunger survivability. Operation times greater than 850 sec will be required along with a turndown ratio greater than 10:1

Performance of the vehicle-level propulsion system will be higher than that of any system yet tested in the U.S. technology base. Nevertheless the committee was encouraged by the good prognosis. The development of this advanced propulsion system is proceeding according to a well-laid-out plan. No technological showstoppers appear to have been encountered to date.

This thrust is well integrated into the long-term development plans of PMA-252, the program manager for the AGM-88E, and it is coordinated with the efforts of the Air Force Research Laboratory Propulsion Directorate.

Recommendation

This program should be pursued until transition takes place and the development of the HSARM begins under PMA-242 sponsorship.

Thrust 7: Weapons Imagery Link

Overview

An ability to control weapons in flight and to redirect them to an emergent target would greatly enhance the ability of naval and joint forces to execute time-critical strike. Such a capability requires a data link that is robust in the face of defensive jamming. The existence of a two-way link between the weapon launch platform and the weapon will permit weapons with imaging sensors to report-back potential targets in the field of view of the weapon's sensor. At a minimum, such a report-back capability will provide positive indications of the weapon's impact on its target and will greatly assist decisions on re-attack.

At present the only available weapon imagery data link is the AWW-13, which is an analog link of limited capability.

The objective of the weapons imagery link (WIL) program is to develop such a link for the standoff land-attack missile, expanded response (SLAM (ER)). This effort is tightly integrated into the ongoing development plans for PMA-258, the program manager for the SLAM (ER).

Findings

The approach being pursued in this thrust is to develop a time-division-multiple access (TDMA) link that will support 25 simultaneous transmissions to and from weapons. Antijam capability will be achieved through frequency hopping and short dwells. Data will be interleaved in many channels. As a result, many frequency channels can be totally jammed, but the data will be fully recovered. "Stacked nets" use different hopping patterns. Although hopping collisions can occur, their impact is handled by forward error correction. The use of short dwells is designed to defeat intelligent jammers. The dwell time will be set to counter the response time of intelligent follower jammers in threat scenarios.

The data link being designed in this thrust is a modern TDMA system that is somewhat reminiscent of LINK-16. The management of this link and processes for subscriber access will be complex but not intractable.

In addition to the issues of link development, this program is addressing a number of associated hardware and software issues that are complex and present some degree of development risk.

As the program is currently configured, it only addresses the development of a data link for the SLAM (ER). The installation of this data link onto other weapons would require specific hardware and software changes. The committee was disappointed to learn of the stovepipe nature of this development.

Recommendations

This thrust is tightly integrated into PMA-258's plans for the SLAM (ER) missile. The program should be supported to its scheduled transition, so that a high-performance modern replacement can be found for the AWW-13 data link.

The committee recommends the development of an expanded CONOPS, including UCAVs or loitering platforms, for this data link.

Thrust 8: Gun Barrel Erosion (and Fatigue)

Findings

Refractory materials and metal matrix composites and functionally graded materials that have been developed under Army and Navy SBIR programs, and Benét Laboratories/Watervliet Arsenal are working on key enabling technologies for this FNC program. The goal is to decrease erosion and increase fatigue life. This is a new program that is just getting under way. Two advanced barrel technologies (refractory and composite materials) are being developed concurrently.

Experimental validation of designs is made difficult because full-scale testing of gun barrels is costly, and there are serious and challenging issues surrounding how one extrapolates and demonstrates fatigue life and erosion rates using scale models to simulate many cycles of gun firing.

Recommendations

A D&I activity to develop scaling laws for fatigue life and erosion rates should be undertaken that will permit small-scale model data to be extrapolated to full scale with confidence. Existing databases and expertise developed by the Air Force on fatigue of metal matrix composites should be utilized in deciding on appropriate materials. New processing techniques—e.g., explosive cladding—should be seriously considered for implementation, and integrated barrel designs that bring the materials and manufacturing processes should be given high priority.

Appendixes

A

Biographies of Committee Members and Staff

L. David Montague, an independent consultant, is retired president of the Missile Systems Division at Lockheed Martin Missiles and Space and a former officer of Lockheed Corporation. A member of the National Academy of Engineering (NAE), he has more than 40 years of experience in the design, development, and program management of military weapons and their related systems. His expertise includes complex systems engineering and systems integration of ballistic missiles, cruise missiles, and unmanned aerial vehicles, as well as exo- and endoatomospheric interceptors engaging these classes of threats. In addition, he is knowledgeable about threat assessment; overhead surveillance systems; cueing technology; battle and engagement management methodology; interceptor design, guidance and control, countermeasures, and discrimination; and the use of directed-energy weapons for defensive purposes. Mr. Montague is a fellow of the American Institute of Aeronautics and Astronautics (AIAA) and a previous recipient of the AIAA's Missile Systems Award. He has served on numerous scientific boards and advisory committees, including the Navy Strategic Systems Steering Task Group and task forces for both the U.S. Army and the Defense Science Board.

Alan Berman is a part-time employee at the Applied Research Laboratory of Pennsylvania State University (ARL/PSU) and at the Center for Naval Analyses (CNA). At ARL/PSU, Dr. Berman provides general management support and program appraisal and supports Joint Counter-Mine Advanced Concept Technology Demonstration; at CNA, Dr. Berman assists with analyses of Navy research and development investment programs, space operation capabilities, information operations, and C4ISR programs. Dr. Berman's background is in defense science and technology, in particular advanced weapon and combat systems. His previous positions include director of research at the Naval Research Laboratory, where he administered broad programs in basic and applied research, including electronic warfare, radar, communications, space systems, space sciences, material sciences, plasma physics, antisubmarine warfare, underwater acoustics, oceanography, electronic devices, and space-based time standards for global positioning systems. Dr. Berman has served on numerous scientific boards and advisory committees, including as co-chair of the NRC's 1999 Review of ONR's Air and Surface Weapons Technology Program.

Victor C.D. Dawson is an independent consultant at the Center for Naval Analyses (CNA), where he previously served as an analyst. A mechanical engineer by training, his background is in naval gun systems and launchers. At CNA, Dr. Dawson directed numerous studies on naval guns and surface ship torpedo defense, as well as conventional strike warfare and future aircraft carrier studies. He was a professor of mechanical engineering at the University of Maryland, where his research interests included structural dynamics and vibration. He also served on the NRC's 1999 Review of ONR's Air and Surface Weapons Technology Program.

Earl H. Dowell is the J.A. Jones Professor and Dean Emeritus of the Edmund T. Pratt, Jr., School of Engineering at Duke University. A member of the NAE, Dr. Dowell's research interests include aerodynamics, air-breathing propulsion, computational mechanics, energy and power technologies, and structural dynamics. His current research interests include the dynamics of nonlinear fluid and structural systems and their associated limit cycle and chaotic motions. Dr. Dowell has served on numerous scientific boards and advisory committees, and he is a current member of NRC's Air Force Science and Technology Board.

Milton Finger is retired deputy director, Department of Defense Programs Office, at the Lawrence Livermore National Laboratory (LLNL). He graduated from the University of California at Berkeley with a B.S. degree in 1957 and has spent his entire career at LLNL, starting as a staff chemist in the Chemistry and Materials Science Division. Mr. Finger's research interests include lethality and survivability of conventional weapons systems, ordnance engineering, propellant chemistry, weapons effects, munitions target interactions, chemistry of explosives, detonation physics, explosives safety and initiation, and computer simulation and prediction of high-explosives performance. He has served on numerous scientific boards and advisory committees, including task forces for the U.S. Air Force Scientific Advisory Board and the Defense Science Board.

Alfred B. Gschwendtner was leader of the Opto-Radar Systems Group at the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL) for many years, where his research interests included coherent laser radar, smart weapons, automatic target recognition, neural networks, infrared search and tracking systems, multisensor fusion, and modeling and simulation. During his tenure at MIT/LL, Mr. Gschwendtner worked on the development and testing of many different weapons systems for the Department of Defense, including air and surface weapon systems for the U.S. Navy. He also served as a member of the Director of Defense Research and Engineering (DDR&E) Technology Area Review and Assessment (TARA) for Weapons for the last four reviews. He is currently a senior staff member in the MIT/LL Aerospace Division and is a member of the NRC Air Force Science and Technology Board.

Dimitris C. Lagoudas is Ford Professor of Aerospace Engineering and associate vice president for research at Texas A&M University. His research interests range from theories of defects in solids to the mechanics of composites and fracture mechanics. His current research interests include active materials and smart structures, as well as multifunctional materials and composites. Dr. Lagoudas has served on numerous scientific boards and advisory committees, and he is a recent member of the Institute for Defense Analyses' Defense Science Study Group.

John (Ted) Parker, retired Vice Admiral, U.S. Navy, is an independent consultant whose background is in military operations relating to ship, air, and missile defense systems. On active duty, Admiral Parker commanded several ships and later a group of over 30 ships. Additionally, he commanded the Operational and Test and Evaluation Force that tested new weapon system designs for the Navy. Prior to retiring in 1989, Admiral Parker served as director of the Defense Nuclear Agency (now the Defense Threat Reduction Agency). He has served on numerous scientific boards and advisory committees, including the NRC Committee for Assessment of Naval Forces' Capability for Theater Missile Defense.

Robert F. Stengel is professor of mechanical and aerospace engineering and director of the Laboratory for Control and Automation at Princeton University. His current research focuses on failure-tolerant and robust control, intelligent systems, and coordinated flight of uninhabited air vehicles. At Princeton, Dr. Stengel was director of the Flight Research Laboratory, where he conducted pioneering experimental research on digital flight control systems, flight computer networking via fiber optics, aircraft flying qualities, and aerodynamic system identification. Before Princeton, Dr. Stengel worked at the Analytic Sciences Corporation, the Charles Stark Draper Laboratory, the Air Force, and NASA. He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA) and of the Institute of Electrical and Electronics Engineers. He received the AIAA Mechanics and Control of Flight Award in 2000.

Verena S. Vomastic is currently a lead engineer with the MITRE Corporation in Colorado Springs, Colorado. A mathematician by training, Dr. Vomastic has specialized in innovative approaches to leveraging all-source intelligence, surveillance, and reconnaissance information for time-critical warfighting tasks and in developing and testing advanced operational concepts for integrated missile defense. Prior to joining MITRE, Dr. Vomastic held leading research and engineering positions at the Aerospace Corporation, the Institute for Defense Analyses, Electrospace Systems, Inc., and the Center for Naval Analyses. Prior to that, she was an assistant professor of mathematics at McNeese State University and a mathematics lecturer with the University of Maryland's European Division. Dr. Vomastic has served as a member of the Naval Studies Board and participated in numerous studies addressing capabilities and technologies for future naval forces.

Stephen D. Weiner is a senior staff member in the Systems and Analysis Group at the Massachusetts Institute of Technology's Lincoln Laboratory. Dr. Weiner's background is in ballistic missile defense, including system and radar design, sensor tracking and discrimination measurements, and interceptor guidance. His current research interests include defense against both theater and strategic cruise missiles. Dr. Weiner has served on a number of government and scientific advisory boards, including the NRC Committee for Assessment of Naval Forces' Capability for Theater Missile Defense.

Staff

Charles F. Draper is a senior program officer at the National Research Council's (NRC) Naval Studies Board. Prior to joining the NRC in 1997, Dr. Draper was the lead mechanical engineer at S.T. Research Corporation, where he provided technical and program management support for satellite earth station and small satellite design. He received his Ph.D. in mechanical engineering from Vanderbilt University in 1995; his doctoral research was conducted at the Naval Research Laboratory (NRL), where he used an atomic force microscope to measure the nanomechanical properties of thin-film materials. In parallel with his graduate student duties, Dr. Draper was a mechanical engineer with Geo-Centers, Incorporated, working onsite at NRL on the development of an underwater x-ray backscattering tomography system used for the nondestructive evaluation of U.S. Navy sonar domes on surface ships.

Ronald D. Taylor has been the director of the Naval Studies Board of the National Research Council since 1995. He joined the National Research Council in 1990 as a program officer with the Board on Physics and Astronomy and in 1994 became associate director of the Naval Studies Board. During his tenure at the National Research Council, Dr. Taylor has overseen the initiation and production of more than 40 studies focused on the application of science and technology to problems of national interest. Many of these studies address national security and national defense issues. From 1984 to 1990 Dr. Taylor was a research staff scientist with Berkeley Research Associates, working onsite at the Naval Research Laboratory on projects related to the development and application of charged particle beams. Prior to 1984 Dr. Taylor held both teaching and research positions in several academic institutions, including assistant professor of physics at Villanova University, research associate in chemistry at the University of Toronto, and instructor of physics at Embry-Riddle Aeronautical University. Dr. Taylor holds a Ph.D. and an M.S. in physics from the College of William and Mary and a B.A. in physics from Johns Hopkins University. In addition to science policy, Dr. Taylor's scientific and technical expertise is in the areas of atomic and molecular collision theory, chemical dynamics, and atomic processes in plasmas. He has authored or coauthored nearly 30 professional scientific papers or technical reports and given more than two dozen contributed or invited papers at scientific meetings. In 2002 Dr. Taylor received the National Academies' Individual Distinguished Service Award and Group Distinguished Service Award for his role as study director of the report *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism.*

B

Agenda for the Committee's Meeting

NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.

Tuesday, May 14, 2002

Closed Session: Committee Members and NRC Staff Only

0800 CONVENE—Welcome, Introductions, Study Plans
Mr. L. David Montague, Committee Chair
Dr. Charles F. Draper, Senior Program Officer, Naval Studies Board (NSB)

Data-Gathering Meeting Not Open to the Public: Classified Discussion (Secret)

0845 NAVAL EXPEDITIONARY WARFARE S&T DEPARTMENT OVERVIEW
CAPT Stephen D. Hancock, USN, Acting Head, Naval Expeditionary Warfare Science and Technology Department, Office of Naval Research (ONR), Code 35

0900 STRIKE TECHNOLOGY DIVISION OVERVIEW
Mr. Michael B. Deitchman, Director, Strike Technology Division, ONR, Code 351

0930 AIR AND SURFACE WEAPONS TECHNOLOGY PROGRAM OVERVIEW
Mr. Gil Y. Graff, Program Manager, Strike Technology Division, ONR, Code 351

1045 HYPERSONIC WEAPONS
Mr. Michael Mumford, Naval Air Warfare Center, Weapons Division (NAWCWD)
Mr. Michael White, Johns Hopkins University, Applied Physics Laboratory

1230 DIRECTED ENERGY
Dr. Eugene Nolting, Naval Sea Systems Command, PMS405

1330 GUN WEAPONRY (PRECISION STRIKE)
Mr. Peter A. Morrison, Program Officer, Weapons Technology Division, ONR, Code 351

1430 TACTICAL TARGETING AND PRECISION GUIDANCE
Mr. Wayne H. Tanaka, NAWCWD
Dr. S. Roger Horman, Naval Surface Warfare Center, Dahlgren Division (NSWCDD)

1545 ADAPTIVE ORDNANCE
Mr. Robert Garrett, NSWCDD

1645 INTEGRATED HIGH-PAYOFF ROCKET PROPULSION TECHNOLOGY
Mr. Scott Fuller, NAWCWD

Closed Session: Committee Members and NRC Staff Only

1730 COMMITTEE DISCUSSION
Moderator: Mr. L. David Montague, Committee Chair

Wednesday, May 15, 2002

Closed Session: Committee Members and NRC Staff Only

0800 CONVENE—Welcome, Opening Remarks, Report Discussion
Mr. L. David Montague, Committee Chair
Dr. Charles F. Draper, Senior Program Officer, NSB

Data-Gathering Meeting Not Open to the Public: Classified Discussion (Secret)

0815 OVERVIEW OF MISSILE DEFENSE AND TIME CRITICAL STRIKE FUTURE NAVAL CAPABILITIES (FNCs)
Mr. David Masters, Program Manager, Strike Weapons Technology Division, ONR, Code 351
Mr. Richard Moore, Noesis Incorporated

0915 CRUISE MISSILE REAL-TIME RETARGETING
Mr. Frank A. Armogida, NAWCWD

1015 MISSION RESPONSIVE ORDNANCE
Mr. Timothy Spivak, NSWCDD

1100 IMAGE AND VIDEO ANALYSIS
Mr. Jesse Hodge, NAWCWD

1230 WEAPON IMAGE LINK
Mr. Keith E. Weisz, NAWCWD

1315 PRECISION STRIKE NAVIGATOR
Mr. Thomas E. Loftus, NAWCWD

1400 ENHANCED TARGET ACQUISITION AND LOCATION SYSTEM
Mr. Bryan J. Freeman, NSWCDD

1500 HIGH-SPEED ANTIRADIATION MISSILE
Mr. Jerome A. Kong, NAWCWD

1545 GUN BARREL EROSION
Mr. Rodney A. Hubbard, NSWCDD
1630 SUMMARY OF TIME CRITICAL STRIKE FNC WEAPONS-RELATED COMPONENTS
Mr. David Masters, Program Manager, Strike Weapons Technology Division, ONR, Code 351
CAPT Stephen D. Hancock, USN, Acting Head, Naval Expeditionary Warfare Science and Technology Department, ONR, Code 35
1645 SUMMARY OF ONR'S AIR AND SURFACE WEAPONS TECHNOLOGY PROGRAM
Mr. Gil Y. Graff, Program Manager, Strike Technology Division, ONR, Code 351

Closed Session: Committee Members and NRC Staff Only

1700 COMMITTEE DISCUSSION
Moderator: Mr. L. David Montague, Committee Chair
1800 ADJOURN

Thursday, May 16, 2002

Closed Session: Committee Members and NRC Staff Only

0800 CONVENE—Welcome, Composition and Balance Discussion
Mr. L. David Montague, Committee Chair
Dr. Ronald D. Taylor, Director, Naval Studies Board
Dr. Dennis Chamot, Associate Executive Director, Division on Engineering and Physical Sciences
0845 COMMITTEE REPORT WRITING—Prepare Draft Report
Moderator: Mr. L. David Montague, Committee Chair
1300 (CONTINUED) COMMITTEE REPORT WRITING—Prepare Draft Report
1700 ADJOURN

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Acronyms and Abbreviations

ACTD	advanced concept technology demonstration
AEROS	advanced eye-safe range-finder observation set
AFOSR	Air Force Office of Scientific Research
AIRS	automatic imagery registration subsystem
Al	alumnium
ARO	Army Research Office
ASWT	Air and Surface Weapons Technology (program)
ATR	automatic target recognition
BAT	brilliant antitank
C2	command and control
C3I	command, control, communication, and intelligence
CEC	cooperative engagement capability
CEP	circular error probable
COEA	cost operational effectiveness analysis
CONOPS	concept of operations
COTS	commercial off-the-shelf
DAMASK	direct attack munition advanced seeker kit
DARPA	Defense Advanced Research Projects Agency
DEW	directed-energy weapon
D&I	discovery and invention
DOD	Department of Defense
DOE	Department of Energy
DPPDB	digital point position database
DPSS	digital precision strike suite

EC	enabling capability
EM	electromechanical
ERGM	extended-range guided munition
ETALS	enhanced target acquisition and location system
FEL	free electron laser
FLIR	forward-looking infrared
FNC	Future Naval Capability
FOAS	focus of attention subsystem
GPS	Global Positioning System
HARM	high-speed antiradiation missile
HCSSL	heat-capacity solid-state laser
HEL	high-energy laser
HSAD	high-speed antiradiation demonstration
HSARM	high-speed antiradiation missile
HMMV	high-mobility multipurpose vehicle
IC	integral charge
IHPRPT	integrated high-payoff rocket propulsion technology
IMU	inertial measurement unit
INOVEC	integrated omnivector cone
IPT	integrated product team
IR	infrared
Isp	specific impulse
IVA	image and video analysis
JCS	Joint Chiefs of Staff
JDAM	joint direct-attack munition
JSIPS-N	Joint Services Imagery Processing System-Navy
JTAMDO	Joint Theater Air and Missile Defense Organization
JTO	Joint Technology Office (DOD)
KV	kill vehicle
LADAR	laser radar
LGW	launch gross weight
LLNL	Lawrence Livermore National Laboratory
MD	Missile Defense (FNC)
MEMS	microelectromechanical system
MRO	mission responsive ordnance
NAVSEA	Naval Sea Systems Command
NAWC	Naval Air Warfare Center

nmi	nautical mile
NRC	National Research Council
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSB	Naval Studies Board
NSWC	Naval Surface Warfare Center
ONR	Office of Naval Research
PTHO	precision target handoff
R&D	research and development
RF	radio frequency
S&T	science and technology
SAR	synthetic aperture radar
SBIR	small business independent research
SHARP	shared advanced reconnaissance pod
SLAM (ER)	standoff land-attack missile, expanded response
TCS	Time Critical Strike (FNC)
TDMA	time-division-multiple access
TLE	target location error
TOF	time of flight
TPS	thermal protection system
TT	tactical Tomahawk
UAV	uninhabited air vehicle
UCAV	uninhabited combat air vehicle
USAF	U.S. Air Force
USMC	U.S. Marine Corps
USN	U.S. Navy
VLS	vertical launch system
WIL	weapons imagery link
WSMR	White Sands Missile Range