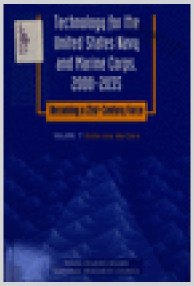

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Preface

This report is part of the nine-volume series entitled *Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force*. The series is the product of an 18-month study requested by the Chief of Naval Operations (CNO). To carry out this study, eight technical panels were organized under the Committee on Technology for Future Naval Forces to examine all of the specific technical areas called out in the terms of reference.

On November 28, 1995, the Chief of Naval Operations requested that the National Research Council initiate (through its Naval Studies Board) a thorough examination of the impact of advancing technology on the form and capability of the naval forces to the year 2035. The terms of reference of the study specifically asked for an identification of "present and emerging technologies that relate to the full breadth of Navy and Marine Corps mission capabilities," with specific attention to "(1) information warfare, electronic warfare, and the use of surveillance assets; (2) mine warfare and submarine warfare; (3) Navy and Marine Corps weaponry in the context of effectiveness on target; [and] (4) issues in caring for and maximizing effectiveness of Navy and Marine Corps human resources." Ten specific technical areas were identified to which attention should be broadly directed. (The CNO's letter of request with the full terms of reference is given in Appendix A of this report.)

The Panel on Undersea Warfare was constituted to address technology issues related to undersea warfare. During the course of its study, the panel paid particular attention to item 3 of the terms of reference:

> Mine warfare and submarine warfare are two serious threats to future naval missions that can be anticipated with confidence and should be treated accordingly in the review. This should include both new considerations, such as

increased emphasis on shallow water operations, and current and future problems resident in projected worldwide undersea capability.

Panel membership included expertise in naval undersea warfare systems design, acquisition, and operations. The panel was augmented with the nation's top ocean acousticians as well as representatives from the nonmilitary private sector.

To carry out its task, the panel met 11 times to receive briefings from service and industry representatives. Briefings and discussions were held with all cognizant systems command program executive officers as well as responsible officials from the offices of the Chief of Naval Operations and the Secretary of the Navy. The panel received several briefings on oceanographic and undersea warfare-related science and technology from the Office of Naval Research and the office of the Oceanographer of the Navy. The panel made field trips to visit fleet commands and laboratories, notably Norfolk, where it was briefed at the flag or unit commander level by U.S. Atlantic Command, Commander Surface Forces Atlantic, Commander Submarine Forces Atlantic, Commander Second Fleet, Commander Strike Force U.S. Atlantic Fleet, Naval Doctrine Command, and the Surface Warfare Development Group. Some of the panel members visited Panama City, Florida, and Ingleside, Texas, to be briefed on mine warfare by laboratory and Commander Mine Warfare personnel. Members of the panel also visited West Coast and Hawaii fleet commands, filing reports upon their return. The panel visited Massachusetts Institute of Technology and Pennsylvania State University, and talks were held with Admiral James Hogg, USN (Ret.) about ongoing work in the Strategic Studies Group at the Naval War College. The chair and vice chair received briefings on relevant special access programs. Because the panel's goal was to produce an unclassified report, not all of the technology issues relevant to antisubmarine warfare and mine warfare are discussed at the same level of detail.

The panel made a special effort to understand the current and projected threat to U.S. national interests in the realm of undersea warfare. A subset of the panel received extensive briefings from the Central Intelligence Agency, the Defense Intelligence Agency, and the Office of Naval Intelligence.

Contents

APPENDIXES

Executive Summary

Acknowledging that the main threats in the realm of undersea warfare, both currently and in the future, are mines and submarines, the Panel on Undersea Warfare focused on those technologies that support antisubmarine warfare (ASW); mine countermeasures (MCM); offensive mining; and intelligence, surveillance, and reconnaissance (ISR) capabilities that support ASW and MCM.

ANTISUBMARINE WARFARE

The Navy's "…From the Sea"[1] and "Forward…From the Sea"[2] documents mark a sea change in Navy strategy by emphasizing battle space dominance and shifting focus from open-ocean, blue water operations to support of joint operations in the littorals. The littorals as an operating area, however, cannot be generalized, because virtually every variety of operating conditions can be found there, from deep (blue) water to shallow (brown) water. Whatever the conditions, it is clear that the undersea environment is an extremely complex and dynamic medium, and naval forces must be able to surveil and control (i.e., dominate) this battle space to the degree necessary to accomplish their mission.

Antisubmarine warfare is one of the Navy's most fundamental core compe-

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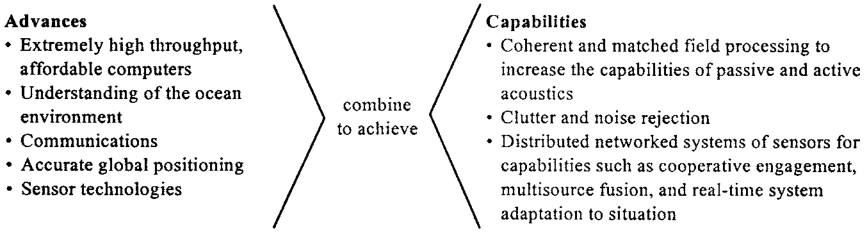
[1] Department of the Navy. 1992. "…From the Sea: Preparing the Naval Service for the 21st Century," U.S. Government Printing Office, Washington, D.C.

[2] Department of the Navy. 1994. "Forward…From the Sea," U.S. Government Printing Office, Washington, D.C.



Advances
- Extremely high throughput, affordable computers
- Understanding of the ocean environment
- Communications
- Accurate global positioning
- Sensor technologies

combine to achieve

Capabilities
- Coherent and matched field processing to increase the capabilities of passive and active acoustics
- Clutter and noise rejection
- Distributed networked systems of sensors for capabilities such as cooperative engagement, multisource fusion, and real-time system adaptation to situation

FIGURE ES.1 Technology advances and capabilities possible by combining them.

tencies, and it must remain so in the face of a submarine threat that will increase significantly—perhaps even dramatically—in the 21st century. This increase, which is being fueled by the proliferation of advanced submarine quieting, sensors, and processing techniques and technologies, could result in the submarine becoming the dominant threat to the accomplishment of naval missions. The psychology of both submarine and mine warfare enhances the effectiveness of the threat, since the adversary has only to possess these weapons to cause arriving forces to operate as if the threat were present and active. The presence of submarines in an adversary's inventory means that effective ASW is needed early on to provide intelligence, prepare the battle space, clear the area for operations, monitor choke points, and protect surface units. The primary weakness in ASW is the detection of quiet submarines. There are also shortfalls in the areas of effective weapons, fire control, and self-defense, but each of these problems generally follows from detection limitations.

Robust technological opportunities exist by which U.S. ASW capabilities can be enhanced to deal with future submarine threats. These advances and the capabilities possible from combinations of them are shown in Figure ES.1. However, resources and proper focusing of research are required to exploit these opportunities. In particular, significant gains in passive sonar appear possible based on larger multidimensional arrays of lightweight, smaller, cheaper sensors and telemetry; multichannel processing exploiting the advancing massively parallel computing technology; and robust characterization or incorporation of the ocean environment. These gains can be applied directly to active acoustics as well.

For tactical passive sonars, it is estimated that current programmed improvements will achieve a 10- to 15-decibel improvement in the near term, with an additional 10 to 20 dB being possible over the time frame of this study if the technological advances shown in Figure ES.1 are exploited. These gains would more than offset the anticipated quieting of future submarines. Passive surveillance sensors should gain 15 to 20 dB from these same technologies, which will support enhanced search capability in both deep- and shallow-water environments.

Historically, advances in ASW come about only as a result of dedicated, long-term research and development projects centered on at-sea operations, testing, measurements, and experimentation. It is precisely these types of R&D projects and operations that are largely absent from current Navy programs and plans.

Future ASW operations will likely evolve in a cooperative engagement context using, simultaneously, the capabilities of multiple assets and sensors on widely dispersed platforms, including those that are space based. In developing the new generations of ASW weapons, strong emphasis should be placed on those technologies that permit rapid attack from submarine, surface, and air platforms. Except for the general advances in information processing, positioning, communications networking, and some sensor materials, there are no specific commercial or alternative military developments that will yield ASW improvements.

MINE WARFARE

As with submarines, mines are a primary option for an enemy who wishes to interfere with or prevent the free movement of joint forces. With the continuing worldwide proliferation of mines and technology, mines will become more sophisticated while remaining a cheap and very effective weapon system. A widespread and/or sophisticated mine threat can readily thwart, halt, or forestall many naval operations, and technology will continue to favor those who deploy mines over those who attempt to detect and destroy them. Nevertheless, the United States must provide the spectrum of MCM tools that allow our forces to move with battle group speed, maneuver in any theater of operations, and operate in support of national objectives.

Since it is highly unlikely that a technology will emerge that can render the mine threat harmless, MCM will continue to be based on a number of discrete systems and techniques arranged in a balanced system of systems. This would include appropriate technologies that range from brute force methods to smart weapons and systems that can be either tethered or autonomous.

The panel believes that MCM systems, concepts, and technologies that are available in the near term, when integrated with present capabilities, will provide the Navy and Marine Corps team with the ability to clear mines in stride. The following major categories of MCM efforts should receive the highest priority:

- A factory-to-seabed intelligence, surveillance, and reconnaissance system is needed that will allow the most effective application of technology when it is required to hunt, detect, and neutralize mines, including destruction or neutralization before mines are laid. The desired ISR system includes imaging sensors and sensors that can see through some obscuration, either deliberate or natural. This system will provide the knowledge of where mines are manufactured and stored, how and when they are moved, and when and where minefields are laid. This allows the elimination of mines before they are laid or the avoidance of mines, delivers information on the types of mines that will be encountered, and provides an understanding of how to defeat those mines that are laid.

- Using advances in sensors, signal processing, and computational power, autonomous or semiautonomous systems can be netted in an undersea surveillance system that uses distributed sensors and small undersea vehicles or bottom crawling devices to provide covert mine surveillance, deletion, and neutralization capabilities. These would be "smart" systems, with communications capability to operate autonomously in the most efficient manner, thereby avoiding personnel and platform losses.
- To meet future threats, a dedicated, organic MCM capability must be made an integral part of naval forces by incorporating appropriate MCM capabilities into battle group combatants and by providing a support ship capable of transporting many small surface and air MCM platforms at battle group speed.
- An aggressive program of naval platform acoustic and magnetic signature reduction should be pursued. Success in this effort will assist in both countering mines and making sophisticated mines increasingly subject to sweeping efforts.
- Because of the density of the threat, lack of time, vagaries of the local environment, and/or need to go ashore at a particular point, there may be situations in which brute force methods of breaching are required. Such methods should be included in the suite of MCM capabilities.
- Anticipating the inevitable retirement of the Avenger-class MCM ship, consideration should be given to a next-generation MCM ship, substantially smaller and lighter than the current classes, capable of operating with improved effectiveness in sea state 4 conditions, and carried on a mother ship capable of transporting up to 10 of the improved MCM units. This support vessel should also carry up to eight of the latest MCM vertical takeoff and landing (VTOL) aircraft; it would include the command, control, and communications capabilities of the current MCM command ship.

Although the Navy's current MCM force may be the most capable in the world, it is inadequate for the challenges of the future. This is a result of the refocusing of the Navy's strategy on the littorals, the lack of a sufficiently aggressive and focused R&D program, and the failure to view MCM as a complete system and provide it with sufficient sustained support from R&D through fleet introduction and operations.

RESEARCH AND DEVELOPMENT PRIORITIES

The Panel on Undersea Warfare considers efforts in the following research and development areas to be particularly important because of the potential improvements they offer to the ASW and MCM capabilities of U.S. forces.

Antisubmarine Warfare Recommendations

- Establish and maintain a dedicated long-term program, centered on at-sea measurements and tests, to provide the science and technology bases for pushing active and passive acoustic array gain to the limits imposed by the ocean. Decades of experience have shown that advances in ASW come about only as a result of such programs.
- Focus passive and active ASW sonar development on exploitation of the ocean's intrinsic coherence and on use of large volumetric arrays, as enabled by massive computational power, miniaturized sensors, and high-bandwidth transmission links, with a goal of 20-dB or greater detectability gains beyond near-term programmed improvements.
- Develop networked, distributed sensor fields, including unmanned platforms (e.g., unmanned underwater vehicles (UUVs), unmanned aerial vehicles (UAVs), and satellites), for both submarine detection and local environmental characterization.
- Develop weapon concepts and technologies that will exploit distributed sensor networks, permit rapid response, and provide more capability against countermeasure-equipped quiet submarines and torpedoes.

Mine Warfare Recommendations

Near Term

- Implement a factory-to-seabed intelligence, surveillance, and reconnaissance capability, using a full set of ISR methods, including surveillance by satellite, atmospheric and undersea manned and unmanned vehicles, submarines, human intelligence assets, and special forces.
- Develop technologies that will provide naval forces with organic MCM capability, including helicopter-compatible sweeping and hunting equipment, remotely operated off-board surface or UUV sensors, and on-board MCM sonars.
- Aggressively pursue the development of so-called brute force technologies that will neutralize mines and obstacles in the very shallow water zone, the surf zone, and the craft landing zone.

Far Term

- Develop technologies for advanced networked sensor and weapon systems consisting of the following:
  - Autonomous and semiautonomous networked undersea systems using small, autonomous undersea vehicles, bottom-crawling variants, and fixed sensors for far-forward covert MCM; and
  - Controllable mines with remote fail-safe command and control (C^2) and selective targeting.
- Develop next-generation MCM ships as small platforms capable of sea state 4 operation, carried by a mother ship capable of battle group speeds. Develop the lightweight hunting and sweeping technologies required for these smaller units.
- Apply reasonable mine shock hardening and effective acoustic and magnetic signature reduction technologies to all new-construction ships.

1

Antisubmarine Warfare

ASW: A CRUCIAL UNDERPINNING FOR FUTURE NAVY MISSIONS

Geography dictates that the United States is a maritime nation. It shares land borders with only two other countries; the remaining nations of the world community lie overseas. The United States has vital economic, political, and military interests and commitments around the globe. Recognizing this fact, the National Military Strategy[1] states that naval forces ". . . ensure freedom of the seas and control strategic choke points . . . provide strategic freedom of maneuver and thus enhance deployment and sustainment of joint forces in theater." "Forward…From the Sea"[2] addresses the Navy's enduring contributions to strategic deterrence, sea control, power projection, forward presence, and peacekeeping.

Fundamental to all of the above is the nation's ability to fight and win on, over, and below the seas. Antisubmarine warfare (ASW), which is one aspect of the ability to fight and win, was designated as one of the Navy's core competencies by the report of the Commission on Roles and Missions of the Armed Forces[3] on May 24, 1995. Highly capable ASW forces that are enhanced through the infusion and implementation of emerging technology and operational innova-

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[1] Joint Chiefs of Staff. 1995. *National Military Strategy of the United States of America*, U.S. Government Printing Office, Washington, D.C.

[2] Department of the Navy. 1994. "Forward…From the Sea," U.S. Government Printing Office, Washington, D.C.

[3] Department of Defense. 1995. *Directions for Defense*, report of the Commission on Roles and Missions of the Armed Forces, U.S. Government Printing Office, Washington, D.C.

tions are required to effect undersea battle space dominance. Whether in peace or war, naval forces must be capable of surveilling and controlling that battle space to the degree necessary to accomplish their mission.

ASW forces will be required to operate effectively both in the open ocean and in the littorals. The challenges of each are different and, in some cases, require unique capabilities. In any future conflict with submarine-capable nations, initial engagements will likely involve littoral ASW. This is an enabling mission that must be carried out prior to the transit of heavy-lift forces through straits and choke points or landing forces ashore. Submarines and mines are two practical means that can be deployed by an enemy to interrupt the flow of joint forces. Naval forces of the future must be able to rid the battle space of the threat posed by hostile submarines to allow for follow-on operations. ASW is also a key element in the nation's strategic posture, since much of the world's nuclear striking power will be based at sea. In many situations, time will be of the essence. To be effective, ASW forces will require system capabilities that allow for accurate remote sensing, targeting, and effective employment of weapons.

Currently, ASW resources are relatively constrained by the overall pressure on military spending, competing warfare priorities, and a continuing debate over the relative significance of the submarine threat. The continuing drawdown in naval forces and current deemphasis on ASW have seriously eroded the Navy's capabilities in this warfare area at a time when potential future adversaries are rapidly acquiring advanced quieting techniques and other offensive submarine technologies.

It is possible that U.S. maritime forces will indeed face a credible submarine challenge within the strategic planning horizon of this study. The who, what, and when of future submarine threats remain uncertain. Suffice it to say, however, that global interest in advanced submarine capabilities continues to provide the clear potential for credible submarine opposition in future conflicts. This opposition can generally be described as sea denial—a capability that is founded in the inherent stealth of the submarine. A small number of unlocated submarines, even with limited capabilities, can pose sufficient threat to disrupt operations of maritime forces. Unlocated submarines can influence events by forcing an advancing battle group to proceed with caution. The primary technical challenge in this warfare area is the requirement to detect increasingly quiet submarines. However, detection is not the only ASW requirement: effective weapons, fire control, and self-defense capabilities are all essential elements of a credible warfighting capability. There are shortfalls in ASW in all of these areas, but each of these problems generally follows from detection limitations.

THE GROWING WORLDWIDE SUBMARINE THREAT

The Russian Federation and the People's Republic of China have publicly declared the submarine as the capital ship of their navies. Many potentially adversarial Third World countries essentially have done the same, including Iran, North Korea, India, and Pakistan. A former Indian Navy submarine flag officer, B.S. Uppal, commented in 1994 that developing nations desire submarine forces because they are a cost-effective platform for the delivery of several types of weapons;[4] they counter surface forces effectively; they are flexible, multimission platforms (e.g., antisurface warfare (ASUW), special forces, intelligence and warning, and ASW); they are covert and thus can be deployed with minimum political ramifications; and finally, they can operate without supporting escorts.

The quieting of advanced non-U.S. nuclear submarines and advanced conventional submarines operating on battery power is now at parity with U.S. submarines. The United States no longer enjoys a comfortable acoustic advantage against the front-line submarines of some other nations. The Russian Federation, for example, continues to build new classes of highly capable submarines and to operate its latest vessels outside of home waters, including waters contiguous to the United States. Russia has recently given additional emphasis to the importance of its Navy, particularly submarines, by creating a budget line for them that is separate from the rest of the armed forces.

The People's Republic of China, which currently has a submarine force that is, for the most part, obsolete, is investing heavily in submarine technology, including designs for nuclear attack submarines, strategic ballistic missile submarines, and advanced conventional submarines expedited by the purchase of KILO-class submarines from Russia. China hopes to leap generations of submarine technology in its ambitious buying and building program.

There are currently more than 150 submarines in the navies of potentially unfriendly countries in the rest of the world other than Russia (see Appendix B for further detail). Forty-five of these are modern, nonnuclear types. Forty-five more submarines are on order worldwide, principally from Russian and German shipyards. By 2030, it is projected that 75 percent of the submarines in the rest of the world will exhibit advanced capabilities. Most of them will have air-independent propulsion systems that allow 30 to 50 days of submerged endurance without surfacing or snorkeling. When these submarines are in a defensive mode, that is, when they do not have to travel great distances or operate at high speed, they have a capability nearly equal to that of a modern nuclear submarine. Quieting technology will likely proliferate, which will render these submarines difficult to find even with the latest ASW equipment, and they may be armed with highly capable combat and weapon systems.

The readiness and proficiency of submarine crews in the rest of the world are improving, and their performance is generally underestimated. Today, training of crews is offered by the countries that export these submarines. Operated competently, these submarines are particularly difficult to locate, especially since

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[4] Comments made to American Systems Corporation personnel on December 14, 1994, during a presentation entitled "A Third World Submarine Perspective" by B.S. Uppal.

they operate mostly in their home waters in a defensive posture, can operate slowly, and can take advantage of acoustic and oceanographic factors to maximize their covertness.

In summary, by 2035, the capability of the United States to project power in the world may be seriously and competently challenged by submarines from major powers (Russia and China) or from a number of potentially unfriendly Third World nations.

OPEN OCEAN TO THE LITTORALS— A WIDE RANGE OF ENVIRONMENTS

Unless a resurgent Russia or an equivalent submarine threat from a country with global reach and ambitions emerges, U.S. ASW operations are expected to be needed principally in the regional waters of adversaries—frequently, littoral waters. This situation will arise because potential adversaries are expected to use their submarines mostly for blockades, mining, and interdiction of surface vessels; these submarines generally will have somewhat limited range and endurance. Air-independent propulsion and, perhaps, the limited proliferation of nuclear propulsion could remove the restrictions to range and endurance. For the foreseeable future, however, identifiable adversaries have neither the need nor the capability for global, far-ranging submarine deployment. Hostile coalitions, however, could conceivably pose simultaneous threats in widely separated regions.

It is a misconception that littoral waters are always shallow. Although it is true that shallow waters are always in littoral areas, an examination of the bathymetry of potential regional conflict areas reveals that the littoral regions encompass the full range of depths from deep to shallow. To illustrate by just two examples, consider first a potential conflict with the People's Republic of China (PRC) over the status of the Republic of China (ROC) on Taiwan. PRC submarines that would be of primary concern to U.S. naval forces would likely be engaged in antishipping operations or possibly threatening U.S. carriers, combatants, and logistical supplies. Such operations would likely occur east of Taiwan out to a radius of perhaps several hundred miles from the Chinese mainland. A look at the water depths in that region reveals that more than 80 percent of the water is deeper than 200 fathoms and only a tiny fraction is shallower than 100 fathoms. The second example is a possible conflict with Iran over the closing or blockade of the Strait of Hormuz. Iran's submarines are based at Chah Bahar and can be expected to operate mostly south or southeastward from that base. Water depths of more than 100 fathoms are reached just 15 miles off the Iranian coast. In oceanographers' lexicon, the waters of Earth's littoral regions cover the spectrum from blue to blue-green to green to brown. A characteristic that is commonly assigned to littoral waters, however, is complexity, exemplified by much shorter scales of variability in both space and time compared to the deep waters of the open ocean. Important features of the littoral regions include tides, irregular and tide-produced internal waves, diurnal variations, variable bottom topography, and a cluttered acoustic and visual background—all of which make ASW operations more difficult.

Effective naval operations in the littoral regions require detailed knowledge and understanding of the maritime environment there. This is a Navy-unique requirement not only for undersea warfare functions such as submarine warfare, antisubmarine warfare, and mine or countermine warfare, but also for amphibious warfare (surf zone, charting, and other near features). Indeed, all naval warfare areas require inputs on weather, ocean condition, aerosols, refraction, and the like.

RECENT TRENDS—REDUCED INVESTMENT IN ASW CAPABILITY

The lack of consensus on a perceived submarine threat and competing warfare priorities, combined with mounting pressure on the overall defense budget, has put the Navy's ASW program at historic low levels in recent years. This deemphasis on ASW, especially on new development, has occurred at the same time that global interest in submarine capabilities has continued apace with steady progress and increased investments in submarine technologies on the part of potential adversaries.

Detecting and then classifying weak signals from future quieter submarines in highly dynamic, complex environments will be extremely difficult. There are technical options that can be pursued, however. The increased availability of computer processing power when applied in combination with new sensor technologies, including nonacoustics and microelectromechanical systems (MEMS), offers the potential of greatly enhanced detection capability. There are no quick fixes, however; a dedicated, focused research effort will be required to develop and effectively deploy these solutions. For example, advanced signal processing techniques must be coupled with a thorough understanding of target and environmental parameters and their variabilities.

Historically, development of enhanced ASW capabilities has arisen out of long-term R&D projects including significant at-sea testing and experimentation. Notable examples include the Critical Sea Test (CST) program, the nuclear-powered ballistic missile submarine (SSBN) security program, the Sound Surveillance System (SOSUS) program, and the Surface Tactical Surveillance System (SURTASS) program. These projects provided the solid foundations for progress in ASW that may be missing in the current restricted funding environment.

ASW will likely continue to be a people-intensive art. Although advancements in automated data fusion and machine-based reasoning will no doubt occur, the human is likely to remain the best integrator of multiple inputs, reaching a conclusion from imperfect data better than any machine. This skill is maintained only by practice, with feedback and learning on a continuous basis. Therefore, regular periods of training at sea, with realistic scenarios and platforms, should be a part of a balanced ASW effort. The increasing sophistication of ASW technology, including the increased automation of ASW assets, will require more highly trained and educated officers and operators, and the Navy must ensure that its personnel have the requisite technical expertise. Expertise in ocean sciences and geophysics will be particularly valuable. The general issue of education and training to enable sailors and marines to effectively utilize the capabilities afforded by new technology is addressed in *Volume 4: Human Resources* of this series.

OCEAN ACOUSTICS: WHAT ARE THE LIMITS?

The challenge to ASW is to increase detection gains faster than the gains in quieting or stealth. The 35 decibels of quieting since 1960 has reduced open-ocean coverage from basin scales to a few kilometers, well within range of weapons. For passive systems the issue now is, Can enough gain be recovered to obtain operationally significant increases in detection ranges? For active systems the issue is, Can the advances in source technology, reverberation reduction, and target identification lead to systems with low false alarms while target strengths continue to decrease? For the next decade, improvements now programmed expect performance gains of 10 to 15 dB for both passive and active improvements. Although less certain, evolutionary gains on the order of 1 dB per year up to an overall gain of an additional 20 dB seem very possible within the 2035 time frame.

There are several bases for these projections:

- Experiments have demonstrated[5,6] that the spatial and temporal coherence of acoustic signals in the very low frequency (VLF) band (<100 Hz) is high, and so wide-band, coherent processing using wide-aperture arrays with a very large number of sensors can lead to high-gain systems. Signal processing algorithms based on coherent, range-dependent propagation codes using real-time environmental inputs now can exploit this coherence.
- The reduction of wide-band threat signatures in the VLF band is difficult because it involves the entire platform, and hull coatings are less effective at damping these long-wavelength acoustic signals. Consequently, it is more likely

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[5] Duda, T.F., et al. 1992. “Measured Wavefront Fluctuations in 1000 km Pulse Propagation in the Pacific Ocean,” *Journal of the Acoustic Society of America*, 92, pp. 339-355.

[6] Munk, W., et al. 1994. “Heard Island Feasibility Test,” *Journal of the Acoustic Society of America*, 96, no. 4, pp. 2330-2342.

that gains in detection capability will exceed quieting and stealth gains in this part of the spectrum.

- The coherence of the noise field increases in the VLF band since shipping is a dominant component. Adaptive processing methods using large-aperture arrays have high performance for both resolution and sidelobe control in suppressing these target-like noises.
- In the past, system performance was constrained by limited computational power. However, relatively high computational power is now available and can be deployed on mobile platforms or with rapidly fielded fixed systems. Similarly, array technology using wide-band, fiber-optic telemetry and miniaturized sensors enables high-performance systems that can exploit ocean coherence.

DEVELOPMENT IMPERATIVES

The development imperative is to improve the gains of sonar devices to enable the detection of potentially hostile submarines that will be characterized by low source levels and target strengths. Sonars have evolved continuously from a few bulky sensors with analog signal processing to arrays with hundreds of miniaturized sensors and high-speed digital signal processing. The understanding of oceanography has grown from the discovery of propagation channels in the ocean to the development of accurate, range-dependent propagation codes and environmental models for noise and reverberation. Similarly, reliable and smart sensing systems can now be deployed using advances in ocean engineering, a lot of hard-won field experience, and rugged very large scale integration (VLSI) electronics. This evolution has been scientifically and technologically intensive; at this point, the easily attainable performance gains have been achieved and even greater exploitation of the science and technology will be required in order to develop future systems than incorporate significant performance gains.

The necessary components of an effective ASW technology development program are as follows:

- Well-posed science and technology;
- At-sea experiments with sensors that are both well calibrated and accurately navigated to provide real-time environmental data;
- Fundamental exploitation of the advances in ocean acoustics, oceanography, and signal processing;
- Robust ocean engineering for their deployment;
- Integration of communications, navigation, and high-speed computation; and
- Highly trained operators.

At the end of the Cold War the merging of these components showed promise for substantial gains in ASW capability, but the momentum has been lost as a result of budget cuts and program cancellations.

Arrays have been essential for almost all sonars. They provide signal gain, noise suppression, and target bearings. Many of the expected future performance gains will likely come from more capable arrays that exploit both horizontal and vertical properties of the signal field. One can look to the oil exploration industry to contemplate what is now possible. There, up to 18 multiline, towed arrays, each with 8-km apertures leading to a total of 2×10^4 sensors, are now routinely used. Two-ship operations with cross-registered arrays are also routine. Finally, mechanisms need to be in place to ensure that competition keeps costs low. In ASW, although specific array designs certainly depend upon the specific application, the imperative for larger, more capable arrays with multidimensional apertures and a very large number of sensors is clear. This is the only means by which additional performance gains can be achieved. More sensors are needed for noise suppression, and larger apertures for better resolution. The acoustic field has a three-dimensional structure that can be resolved only with multidimensional arrays.

The spatial and temporal coherence of both submarine signals and ambient and reverberation noises is the fundamental acoustic attribute that will enable the development of high-performance ASW signal processing systems. Experiments have demonstrated that the ocean supports much greater acoustic coherence than is now exploited by current operational ASW arrays if one compensates for source-receiver motion effects and makes use of accurate propagation models. This is especially so in the VLF bands where acoustic signals propagate most efficiently and where submarine quieting is most difficult to achieve. High coherence implies the potential for high processing gains. Several experiments have achieved signal gains greater than 40 dB, and a few greater than 50 dB, in contrast to the 20- to 30-dB gains realized in present systems. Similar gains can be expected against coherent directional noise fields such as those found in high-clutter or battle group environments. Table 1.1 shows the apertures scales that may be required to fully exploit the spatial coherence of the ocean.[7-9]

Similarly, the temporal coherence of the ocean can be exploited further. Oceanographic processes such as internal waves and sea surface motion introduce time fading, as well as multipath and boundary interactions, leading to time spreading which limits coherence; nevertheless, careful compensation for motion can push the processing closer to the limits of temporal coherence. Experiments

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[7] Baggeroer, A., W. Kuperman, and P. Michalevsky. 1993. "An Overview of Matched-Field Methods in Ocean Acoustics," *IEEE Transactions, Journal of Ocean Engineering*, 18, pp. 401-424.

[8] Flatte, S., et al. 1991. "Impulse-Response Analysis of Ocean Acoustic Propagation," pp. 161-172 in *Ocean Variability and Acoustic Propagation*, J. Potter and A. Warn-Varns, eds., Kluwer Academic Publications, Norwell, Mass.

[9] Carey, W.M., J.W. Reese, C.E. Stuart. 1997. "Mid-frequency Measurements of Signal/Noise Characteristics," *IEEE Transactions, Journal of Ocean Engineering*, 22, pp. 548-565.

TABLE 1.1 Aperture Scales Required for Sonar Arrays

Low frequency, deep water	Horizontal	1,000 wavelengths
	Vertical	100 wavelengths
Low to mid frequency, shallow water	Horizontal	200 wavelengths
	Vertical	20 wavelengths

here suggest coherent integration intervals on a scale of 10^5 kiloperiods (>1/2 hour at 50 Hz) for deep water and 10^4 kiloperiods (>3 min at 500 Hz) for shallow water are attainable.

Source-receiver and target motion leads to Doppler and differential Doppler effects that are robust phenomena in many ASW scenarios, yet sonar systems do not exploit them to nearly the extent used in space-time processing and synthetic aperture radar systems. An acoustic version of synthetic aperture radar has been a long-sought goal for sonar systems. Three principal obstacles have frustrated achievement of this goal: (1) For a ship to be able to steer itself at sea, it must travel fast enough for its control surfaces to be effective. The ratio of the average cruising speed of a ship to the speed of sound in water is relatively high for sonar compared to the relevant ratio for ship radar (10^{-3} for sonar versus 10^{-6} for radar), and this limits the maximum range. (2) Reverberation persists for a long time, which leads to low pulse repetition frequencies. (3) Navigating the sensors to the small fraction of a wavelength needed for coherent beam forming is very difficult. Advances in precision navigation using the global positioning system (GPS), miniaturized sensor positioning systems, and coherently navigated receiver arrays, either towed or hull mounted, can mitigate these difficulties for both passive and active sonars, especially at very low frequencies. More generally, fully navigated beam formers (i.e., those that track targets in position and velocity) can lead to longer coherent processing intervals, and hence, higher gains. In radar this is termed space-time beam forming and leads to impressive noise suppression for both clutter and jamming, yet it has not been explored in sonar.

Coherent sonar signal processing can be considered a generalized form of matched filtering, so that spatial and temporal replicas, or matching signals, are required for implementation. The processing for operational arrays, whether mobile or fixed, is based on narrow-band, plane wave fronts for passive systems plus direct replica correlation for active systems. The ocean waveguide introduces vertical inhomogeneity and multipath and modal dispersion, as well as differential Doppler effects in acoustic signals. These effects are very significant for long-range, deep-water VLF and for shallow-water propagation. Consequently, plane wave beam forming and replica correlation processing do not lead to the gains of a fully coherent processor. Acousticians have developed numerical codes for this waveguide propagation. They enable fully coherent processing in these environments with a generalized form of beam forming, usually termed matched-field processing. With this technique, the complexities of the acoustic waveguide can actually be used to improve array performance. In fact, these methods are most effective when the arrays have a vertical extent. This fully coherent processing technique incorporates environmental data for wide-band prediction of the signal and noise fields. It also uses coherence limits of the propagation to establish array lengths and coherent processing intervals, as well as the division between the coherent and incoherent sections of the sonar signal processor.

Target detection is a function of both the signal and the noise fields. The acoustic noise field for both passive and active systems has considerable structure that can be exploited by modern adaptive algorithms. The noise field for passive systems can be very directional because of commercial shipping and nearby friendly ships, and this is amenable to cancellation techniques. Similarly, the reverberation in an active field is governed by water column multiple reflections and bathymetric features that can also be mitigated. Doppler phenomena are important features of a noise field as well, and they have not been exploited in sonar systems to the extent that they have in radar systems.

Oceanographic models are now used to predict quantities such as transmission loss and noise levels, which are entries in the sonar equation. Although there has been progress toward greater integration into the sonar system, such as the real-time implementation of the parabolic equation and on-line ambient noise models, the environmental data now available from real-time sensors, databases, and satellite observations are not well utilized for optimizing sonar performance. More importantly, oceanographic data generally are not brought to bear on sonar signal processing problems. For example, virtually all of the algorithms now in use are based on a plane wave signal model, such as that used in radar. Acoustic propagation in the ocean is significantly more complicated than the propagation of microwave radar signals. Nevertheless, there has been substantial progress in the development of codes for predicting acoustic propagation when accurate environmental models are available. Although random ocean dynamics and complicated boundaries will always preclude exact models, the limits on environmental data accuracy must be pressed to exploit the coherence of the signals. Oceanography coupled with accurate propagation models can permit the extraction of useful signals from what would otherwise appear to be noise. Advances in the technology of sensors deployed from either moored or remote vehicles, tomographic systems, and satellites will continue to make these data even more useful for improving sonar performance.

Adaptive beam forming has long been pursued in the sonar research community; yet with a few exceptions, it has not been employed routinely in operational systems. Until quite recently, improvements in adaptive beam forming techniques have not justified the added complexity and computational resources required, and performance could actually be degraded if adaptive beam forming was implemented incorrectly. The utility of adaptive algorithms depends on the ambient noise field and array geometries. Adaptive algorithms are most useful in directional fields such as those with high clutter. Although this technique was initially advocated as a means to enhance the resolution of short arrays, its use for sidelobe control in the presence of strong interference and for matched-field processing is very important. ASW against quiet, stealthy targets is always a weak signal detection problem, so the suppression of sidelobes, even low-level ones, is important. Although there are still limitations for wide-band arrays with a large number of sensors, the computational capability to implement adaptive systems has grown dramatically and should continue to increase. Adaptive beam forming has been a topic of extensive research and development, including the development of arrays with a large number of sensors. Now, there is greater understanding of the algorithms and their limitations, and new algorithms are being developed, so that more robust and stable implementations of adaptive beam forming are expected to be available soon. It is important to emphasize that fully coherent processing and adaptive processing are different issues, although they can reinforce each other.

The rapid pace of development in acoustics, oceanography, signal processing, and ocean engineering relevant to sonar applications should enable a shortening of the development time between the demonstration of the engineering feasibility of advanced sonar techniques and their implementation. The long development times for new sonar systems, which have in the past often spanned a decade or more, are no longer acceptable—long development times do not allow the Navy to respond rapidly to changing missions and needs. There should be continuous process of system development with a build-test cycle included as a fundamental part of the process. It is anticipated that the signal processing capability will continue to grow rapidly since it is often coupled to commercially driven products. New system architectures should be flexible and well documented so that new hardware and software developments can be implemented quickly and easily. There will likely be fewer versions of sonar sensor hardware because the design, testing, and implementation are unique to ASW and thus more costly; consequently, such hardware should be designed to be modular and flexible, making use, for example, of widely compatible interfaces. The entire development cycle should incorporate a continuous evolution of building and at-sea testing, with extensive support by science and engineering ship riders to complete the design feedback process. Prototype systems will likely be too complex to permit effective evaluation by operators trained on legacy systems.

The training of sonar operators and officers is currently not adequate to meet the near-term future threats anticipated by the panel, and the complexity of future systems will only exacerbate this shortcoming. The current practice of training new enlisted personnel in oceanography for only two weeks is certainly not enough for understanding its impact on ASW performance across the range of potential operating environments. Investment in the experience of sonar chiefs will continue to be important. Officers will need much more extensive training in acoustics, oceanography, and signal processing, and a strategy for providing this education is required. Such intensive training will no doubt be costly, but it is considered necessary if future high-performance ASW systems are to be deployed effectively. This type of comprehensive and extended training cannot be acquired in short order with the onset of a crisis.

SENSORS FOR MOBILE PLATFORMS

With the diminished effectiveness of fixed systems for basin-scale coverage, lightweight sensor arrays that can be deployed from mobile platforms have acquired added importance. The SURTASS towed array system, particularly the latest twin line version, now has the widest area coverage for regional control. Towed arrays, forward spherical and cylindrical arrays, and conformal arrays from both submarines and surface ships provide tactical ASW. Since these systems are mobile and can be deployed rapidly in areas of potential conflict, they most likely will form the major components of future ASW systems. The experience of the offshore oil exploration industry suggests that arrays of up to several kilometers long with 10 or more multilines, more than $\sim 2 \times 10^4$ sensors, and multiship operations are within the realm of current technology; there is every confidence that the rates of massively parallel digital signal processors soon will be adequate for real-time processing with such systems.

Towed array technology has advanced rapidly with longer, multiline systems that have an increasing number of sensors. For submarine-based ASW, the thinline TB-23 is routinely deployed. The TB-29 is longer and has a sensor location system. It is now available on a few platforms and will be deployed on the *Seawolf* and the nuclear-powered attack submarine, new version (NSSN). It will be the operational submarine-towed array for the foreseeable future. Experiments with adaptive beam forming on both arrays are demonstrating impressive results especially for cluttered environments. For surface ships, the twin line SURTASS has been deployed, and systems with multiline arrays are in advanced development. Multidimensional array geometries lead to both gain and better target motion analysis because they break the right-left ambiguity of a single line array without the need for ship maneuvering; moreover, these systems have employed state-of-the-art sensor location systems that maintain signal gain and adaptive array processing for superior noise suppression performance. A very important aspect of these arrays is that they can operate in the VLF band where it is most difficult to suppress the threat signature. Although there are significant engineering difficulties, multiline submarine arrays should be examined for the next-generation array beyond the TB-29.

Towed arrays are also an essential component of the Navy's mobile active systems that have evolved from the Critical Sea Test and Low-Frequency Active (LFA) programs. Source levels today are high enough so that the performance of active sonars is largely a measure of reverberation, or clutter, suppression. This is now usually accomplished by resolving targets along a beam in range with wide-bandwidth signals or in Doppler with long-duration signals or with a combination of the two. The same technology of longer, multiline arrays with very accurate sensor positioning that will likely be the foundation of improved passive sonar systems will also serve to enhance the performance of active systems.

Bistatic active systems offer many advantages for reverberation suppression with mobile systems, as has been demonstrated in several tests in the LFA and CST programs. The same issues of increasingly capable arrays that more fully exploit the coherence of acoustic signals in the ocean is just as relevant to bistatic systems. Since active systems reveal the location of the source signal, their use is a liability for submarines. The technology for expendable, leave-behind sources that can mitigate this restriction has recently been developed, so submarines can now operate in bistatic modes. There is still a liability associated with the use of active sonar deployed on an off-board vehicle, however. It is possible under some circumstances for an enemy submarine to acquire the echo of one's own submarine from the active sonar signal generated by the off-board source.

One of the major advances in the last decade has been the recognition that the vertical structure of both signal and noise fields represents an opportunity to improve ASW signal processing. Although this has long been recognized by using arrays at endfire instead of the usual broadside geometries, the introduction of towed vertical apertures has led to impressive experimental results. This technique has been carried out using vertically distributed multiline arrays or the purposeful slanting of an extended SURTASS array.

The forward spherical and cylindrical arrays are useful at mid frequencies where they provide fully directional resolution. Although it is unlikely that the size or number of sensors on these arrays can be increased, their performance can be improved with state-of-the-art signal processing. Full-area, conformal arrays distributed over a large extent of a submarine offer wide apertures and are not encumbered by the tactical constraints associated with long towed arrays. They are subject to structural self-noise, however, as well as flow noise at high speeds. There have been a number of development programs for conformal arrays, for example, advanced conformal submarine acoustic sensors (ACSAS) and conformal acoustic velocity sensors (CAVES). The wide-aperture array (WAA), which has already been deployed, has demonstrated the utility of depth-of-field beam forming in tactical scenarios. Advances in low-noise sensors and signal processing should improve conformal array performance at mid frequencies.

High-gain arrays require accurate sensor positions and well-calibrated response functions to avoid signal gain degradation and large cancellation ratios. This is especially important with highly directional noise interference such as nearby shipping lanes or a nearby friendly battle group and with high-sidelobe beam formers such as those found with vertical apertures. Sensor location systems for towed arrays have advanced significantly using GPS, high-frequency acoustic ranging, heading sensors, and tracking algorithms that are based on the known dynamics of the array. Some of these location systems have been incorporated or are now being retrofitted. Minimizing positional uncertainty is imperative for both passive and active sonars to (1) push array gains to their environmental limits, for high gain; (2) exploit vertical arrays; and (3) enable beam forming while maneuvering. Similarly, sensor response variability caused by structural inhomogeneities leads to the same liabilities in achieving high gains for mounted and conformal arrays. This can be minimized by incorporating accurate test range and structural acoustic models into the array processing algorithms.

The technology for towed arrays has two major components that ultimately limit their size and number: the sensors themselves and the signal telemetry. These components are also important elements of hull-mounted arrays. Sensor technology has made tremendous advances with solid-state electronics. The transduction unit itself is now much smaller, and VLSI digitizers at the sensor eliminate some of the limitations of analog telemetry. More importantly, when used in conjunction with fiber-optic technology, digital telemetry enables an order-of-magnitude increase in array size and sensor number. Telemetry from the sensor to the on-board signal processor typically has used twisted pair cables. When there are a large number of sensors, this type of cabling resulted in large-diameter arrays and reliability problems simply because of the number of wires and connections. This in turn required large winch diameters and awkward handling systems. Fiber-optic telemetry changed all of this. Cable diameters are smaller, and so longer arrays can fit on the same size winch, and bandwidths far exceed twisted pairs, so that more sensors can be employed. This enabling technology has already been demonstrated in the oil exploration industry where it has dramatically improved array performance. It is just making its impact felt on passive and active sonars used in naval applications.

Hull-mounted arrays are particularly prone to self-noise problems. Self-noise is dynamic and dependent on speed, depth, operating conditions, machinery configurations, and so on. It adds to the clutter environment on displays and distracts operators. Modern adaptive algorithms are very useful for both monitoring and canceling self-noise fields.

The real-time acquisition of environmental data is an imperative, but challenging, task for a mobile system that must be capable of operating anywhere in the world. The research community has gone to great lengths to acquire such data, but the requisite oceanographic data are both site and time specific, with many scales of variability, and tend to be undersampled in both space and time. The important issue is that up-to-date site-specific environmental data must be incorporated in the deployment of mobile sonar if high detection gains are to be realized.

Operational beam formers for towed arrays assume the array geometry to be straight and horizontal aft of the tow ship, whereas in reality there is always some deformation from this geometry. This is now measured by heading and depth sensors with varying degrees of success. The passive TB-23 and the active LFA arrays can monitor gross deformations, and recently developed systems, such as the TB-29 and the twin line SURTASS, enable compensation in the beam former. A major limitation in current systems is that beam forming cannot be carried out when the ship is maneuvering, which can result in downtimes as great as 50 percent. If the turn is gradual enough, the increase in self-noise is not dramatic; therefore, there is no fundamental limitation to implementing beam forming during a maneuver if the sensor positions are measured accurately. Increased availability of beam-formed data could have a significant impact on tactics. There are also a number of potentially useful properties of deformed towed arrays that deserve exploration. The right-left ambiguity can be distinguished with horizontal deformations, and the introduction of vertical tilt leads to the possibility of using matched-field processing.

It has been recognized for some time that wide apertures can provide instantaneous passive ranging at mid frequencies. Several systems have been tested, and the beam forming for the WAA implements range-dependent focusing. Several towed array experiments have demonstrated this as well. Passive ranging information is very useful for tactical ASW and should be a feature available in all future beam forming systems.

Submarine detections on mobile platforms are still made by human operators despite extensive research on automated detection, pattern recognition, and neural networks and this is likely to remain the situation for some time. More capable sonars will provide both more resolution and more varied means of analyzing the data. This will significantly expand the search space dimensionality, but there is a real danger of overloading the operators with information. Advances in database management and display enhancements can improve operator performance so that the full potential of the sonar can be used. Some aspects of the detection process could possibly be automated enough to lead to manning reductions.

SENSORS FOR FIXED SYSTEMS

The bottom-mounted SOSUS arrays were one of the major elements of the ASW effort during the Cold War. They provided enough gain and directionality for basin-wide surveillance to be maintained at ocean basin scales in the theaters of interest. Now that the threats are quieter, basin-scale coverage of low-speed targets is no longer possible. The High Gain Initiative was the last effort to regain basin-scale coverage, but it was cut short with the end of the Cold War. Currently, there is seldom a need for ASW throughout the ocean basins, and the Navy is on a track of abandoning SOSUS and its associated support infrastructure. Nevertheless, with the submarine being the capital ship of choice for many countries, one must seriously consider the need for a SOSUS capability within the 2035 time frame.

Now and for the near-term future, the potential operational theaters are regional, where it is difficult to deploy permanent array systems. ASW control in critical sea lanes, for carrier battle groups and forward troop introduction, requires the ability to achieve regional acoustic superiority. This indicates a need for rapidly and covertly deployable array systems with lifetimes on the scale of a year and regional coverage of hundreds of square kilometers, containing both bottom-mounted and moored vertical arrays. Miniaturized sensors with numbers on the scale of 10^4, digitized in situ and connected with wideband, fiber-optic telemetry, are needed. Accurate sensor positional calibration for the horizontal array sensors and mooring location of the vertical arrays using either navigation surveys or sources of opportunity are necessary. The vertical arrays would also require tilt and compass sensors for dynamic positioning in response to ocean currents. The advanced deployable system (ADS) and the fixed distributed system (FDS) are bottom systems that have these general features, but the addition of the vertical apertures is important.

There is need for a short-lifetime, very rapid, air-deployable array system for situations in which there is not enough time to field an ADS or FDS system. A high-gain sonobuoy-type array system is needed since the approach of a grid of single sonobuoys does not have enough sensitivity for current and projected threat levels. Each sonobuoy would contain a vertical array, and the entire network would be navigated by a real-time positioning system. At one time the Navy developed the star tracking rocket altitude positioning (STRAP) and vertical line array difar[10] (VLAD) systems, which had this type of construction. The STRAP had single sonobuoy sensors instead of vertical arrays and far fewer sensors, but it addressed many of the important technical issues, including sensor positioning. The VLAD sonobuoy had a small vertical array for improving the signal-to-noise ratio (SNR). The sensor technology has now advanced significantly.

The coverage that a fixed system can provide against modern quiet threats will not have basin scales, but the performance can be maximized with imperatives described earlier. Wide apertures with sensor numbers far exceeding those of SOSUS, the use of fully coherent processing with accurately navigated arrays, adaptive beam forming, and the exploitation of Doppler all can be used with the same measures of effectiveness. Fixed receivers with active sources also can be used advantageously. ASW detection depends exponentially on signal-to-noise ratio; even 5-dB increases are important and 15- to 20-dB gains are dramatic. Ocean acoustic propagation is ducted, so recovering a significant fraction of basin-scale coverage is certainly feasible.

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[10] Difar is a type of directional sonar.

SCIENCE AND TECHNOLOGY ISSUES

Several science and technology issues must be addressed to ensure the continuous evolution of improved performance for both mobile and fixed sonar systems. Although signal processing algorithms and computational capabilities are necessary for a high-performance sonar, the acoustic-oceanographic coherence is what ultimately sets the limits. The science and technology issues for coherence have several environmental contexts.

Littoral waters, where these sonars must operate, can be quite shallow (10 to 200 m) or deep (kilometers) and include a range-dependent shelf break. In shallow water and on the shelf, strong horizontally anisotropic internal waves driven by tidal and topographic forcing, usually with a diurnal period, can modulate sound speed profiles dramatically. In upslope-downslope geometries these can precipitously interrupt surface duct propagation and impact coherences through mode coupling and/or ray path fluctuations. When bottom refraction sound speed profiles are present, bottom interaction can significantly impact coherence. Even well-lineated, constant-depth, shallow water introduces problems because of differential absorption; the complexities of rapidly range-dependent slope with high geologic roughness are even more challenging.

Coherence in deep water is greater than in the littoral, especially when the signals are not bottom interacting. This presents an opportunity to significantly increase detection ranges by pushing coherence to the limits. VLF deep-water experiments have demonstrated significant frequency dependence on coherences, with those in the lower edge of the band demonstrating remarkable ray-mode coherence, whereas those in the upper section have different coherences for the high-angle paths and the ducted paths. The cumulative effects of internal waves appear to be the problem, but there is a great deal of controversy about this issue. Bottom interaction has received less consideration; but it is an unavoidable issue, especially for active systems.

It is useful to examine what has been learned from some recent programs to suggest some of the needed R&D. The programs discussed below are concerned primarily with deep-water acoustic phenomena, as U.S. ASW efforts have, in the past, been focused on deep water operations. Some of the knowledge gained from these programs is applicable to operations in shallow water, but, in general, additional R&D will be required to extend ASW capability to shallow waters.

- The High Gain Initiative (HGI) was a response to the appearance of quiet threats and the loss of basin-scale coverage by SOSUS and SURTASS. It was a fixed system that several vertical array geometries spanning a large fraction of the water columns and applied matched-field processing. Environmental monitoring was extensive, and there were ancillary tomographic experiments. Matched field methods are a generalized form of beamforming when the vertical multipath-multimode features of the signal field are significant. The first successful experiments with matched-field processing were conducted in the Arctic at ranges of 250 km. The HGI demonstrated that in the VLF realm, the ocean coherence supported matched-field processing. Augmented sources were resolved in depth to within 50 m and in range to within 2 km at detection ranges of 1,000 km at 25 Hz. Since the HGI, there have been several experiments with vertical arrays that have matched-field processing in both deep and shallow water.

- The Defense Advanced Research Projects Agency (DARPA) 3X experiment used three concatenated SURTASS arrays to create a very long aperture. The ocean supported fully coherent processing over this extended horizontal aperture, which was approximately 600 wavelengths in extent. Wave front curvature and range-dependent beam forming were successful in near-field and far-field targeting. The array was purposely allowed to deform so that it had a vertical extent, and matched-field processing was applied. Sources were resolved in range and depth at long ranges, again suggesting the gains obtained with fully coherent processing.
- The Heard Island Acoustic-Tomography-Climate (ATOC) experiments for acoustic monitoring of ocean climate have demonstrated coherence at several-thousand-kilometer ranges. During the Heard Island Feasibility Test, matched filtering was successfully carried out for 3-minute signal durations at 5,000-km ranges. Phase shifts induced by source motion were tracked to within a fraction of a wavelength at ranges of up to 9,000 km. The ATOC experiments demonstrated coherent matched filtering for more than 20-minute signal durations, and vertical beam forming was coherent for the deep reflection and refraction paths at 5,000-km ranges. The surprising result was the modal scattering of the very energetic axial signals. Overall, although the source level was high compared to current threat signatures, these experiments demonstrated that the ocean supports coherent propagation and passive localization at very long ranges.
- The CST and LFA programs have been the focus for active sonars over for the last decade. High-powered, vertically transmitting arrays and towed horizontal receiving arrays have been used to resolve the spatial structure of the reverberation and submarine target strengths. The Acoustic Reverberation Special Research Program (ARSRP) investigated fundamental properties of acoustic scattering. The arrays of the CST-LFA system demonstrated the importance of high-resolution bathymetric maps of the bottom geology and oceanographic models for the insonification. These have led to environmentally driven models for the coherence of the reverberation and the limits on target detection by range gating. Similarly, models for the signal modulation due to surface waves and entrained bubbles led to environmental models for Doppler coherence and limits on target detection using narrowband signals.
- The twin line SURTASS experiment used two parallel towed arrays with a sensor positioning system. It implemented a simple form of adaptive beam forming, with the array shape compensation from the positioning system. The gains with even this simple form of adaptive beam forming were impressive when operating in a high-clutter, shipping lane environment. Ranges exceeded

those of all other systems operating simultaneously. The right-left ambiguity was broken, which led to much less clutter on the displays and better operator performance.

These and other experiments suggest some of the critical issues in acoustics, oceanography, and signal processing for future ASW systems.

Acoustics

- *Coherence scales.* Although there have been many theories and experiments addressing the issues of spatial and temporal coherence, the limits have yet to be established for the environments and spectral bands where ASW operates. Careful experiments with accurate environmental data and modeling have frequently revealed coherence scales larger than those predicted by theories and simulations. Data for horizontal and vertical apertures, low and high frequencies, and shallow and deep water are all necessary.
- *Noise fields.* The ambient noise field structure is a key issue in ASW. If the noise is directional or has spectral features, these can be exploited to improve ASW detection performance. The coherence of the noise field is just as important as that of the signal in signal-to-noise measures. Important aspects of the noise include its dependence on environmental parameters, excitation mechanisms such as shipping and natural processes, frequency dependencies, and coherence. It can also be used to make environmental assessments much like ocean weather.
- *Reverberation processes.* Most active systems are limited by reverberation noise, which is caused primarily by bottom and surface scattering and sometimes by sea life or other objects in the water column. Acoustic models for wideband range resolving and very narrowband, Doppler resolving scattering for systems operating in monostatic and bistatic geometries are necessary if one is to take advantage of large-aperture arrays.
- *Doppler processes.* The temporal structure for moving source-receiver is important for synthetic aperture arrays, fully coherent matched-field processing, forward-scattering systems, and detection by Doppler gating for active systems. It has a complicated dependence on surface and internal ocean waves and source-receiver motion in a multipath/multimodal, range-dependent medium; nevertheless, experiments have demonstrated a remarkable robustness for Doppler phenomena over very long ranges.
- *Range-dependent and three-dimensional propagation.* Acoustic propagation is strongly dependent on the temporal and spatial variability of the medium even at modest ranges. Although there has been significant progress starting with the parabolic equation, a need remains for range-dependent propagation codes that can accommodate rough and elastic seabeds, surface wave modulations, and internal wave scattering. There are many ASW sites in the littorals, but

relatively little work has been done on the shelf regions where range dependence is very significant. Three-dimensional effects such as slope refraction and horizontal refraction are also just beginning to be appreciated. Propagation modeling often separates into two approaches—deterministic and stochastic; since both are inevitably necessary, better coupling between the two is sorely needed.

- *Wide-band signal models*. Almost all acoustic modeling has been based on narrow-band representations with Fourier synthesis used for wide-band signals. Wide-band representations are needed for all active systems that use travel times and for passive ranging systems such as matched field. Wide-band representations in all bands (VLF, low frequency [LF], and medium frequency [MF]) now press the limits of computational capabilities when range dependence, time variability, and scattering are present.

Oceanography

- *Environmental data and models*. Oceanographic data are undersampled in space and time, and so a variety of strategies must be used to provide environmental inputs to the acoustics. These include high resolution; seasonally dependent atlases; on-board, off-board, and cooperative sampling; satellite data; and tomographic networks. All must be coupled with oceanographic models for data assimilation.
- *Ocean coherence*. Acoustic coherence is driven by the spatial and temporal variability of the ocean. Models exist for wave processes at all scales of variability—spatially from basin scales to microstructure and temporally from years to seconds; however, they are usually not specific enough to use for predicting acoustic coherences.
- *Volume and scattering physics*. Acoustic wavelengths for ASW are usually between 1 and 100 m, which sets the scale needed for the scattering physics. Ocean environments are seldom measured to such scales in any deterministic way, so random models are necessary to make robust acoustic predictions. Oceanographic models for the sea surface, internal waves, and bathymetry exist; however, they require further development to extrapolate their use down to acoustic wavelength scales and environmental data to constrain the parameters in the models.

Signal Processing

- *Algorithms for wide-aperture, high-density arrays*. Large-aperture arrays are capable now of resolving the complexity of multipath, multimodal acoustic propagation. The use of multidimensional geometries such as multiline towed arrays, large networks of bottom arrays, and curtains of vertical arrays further advances this capability. This leads to many opportunities to improve the signal and array processing for ASW from the relatively straightforward, such as range-dependent (depth-of-field) beam forming, to the complex, such as fully coherent, wide-band, matched-field processing. The paradigm of linear arrays with plane wave signals has been the basis for virtually all Navy array processors and has led to well-established design criteria for beam formers. With multidimensional arrays operating in a complex, inhomogeneous acoustic medium, these design criteria are no longer appropriate. Algorithms for side-lobe control, wide-band signals, space-time and Doppler processing, synthetic apertures, and robustness are all needed for fully coherent processing with these arrays.

- *Real-time, environmentally adaptive algorithms*. Adaptive array processing offers the potential for higher signal and noise gain, clutter reduction, and detection at lower signal-to-noise ratios. It is needed for multidimensional arrays and matched-field processing for sidelobe control. For passive sonars, larger arrays resolve more directional sources and adaptive processing provides cleaner displays and easier track identification, whereas for active sonars they can mitigate reverberation. Adaptive algorithms have superior resolution, which can improve the accuracy of solutions for target motion analysis, but they are computationally intensive and not applicable in all environments. Incorrect implementations can degrade performance. They can be sensitive to sensor calibration, positioning errors, and environmental modeling errors, as well. For dynamic noise environments, the time required for the adaptation with arrays having a large number of sensors can be problematic. Promising approaches include dynamic dimensionality reduction, calibrating the medium with probes such as self-cohering signals, and conjugate field methods as well as alternative signal representations such as wavelets. Research to exploit fully the capabilities of both the arrays now being deployed and the even larger ones to follow must accompany development of the arrays themselves.

- *Postprocessor algorithms*. The emphasis in signal processing is usually on the coherent front-end beam forming and matched filtering, yet the postprocessor that performs an incoherent combination of these outputs across frequency for a threat spectrum and over time for a track hypothesis provides a substantial fraction of the overall processing gain. In addition, the postprocessor provides the track parameters for target motion analysis solutions. The computational resources for large-dimensional search spaces, which include the spectral bands and up to five spatial parameters—azimuth, range, and the velocity vector—are now available; thus, algorithms such as "track before detect" for lower detection thresholds, dynamic tracking for clutter management, and classification for target identification can now be carried out in real time. Tracks are usually established by identifying a directional signal that emerges above a local noise level. The template design for this is one of the subtle, but very important, aspects of low SNR detections, and its effectiveness depends on the ambient noise environment. Both components of the postprocessor will have to respond to the demands of higher-resolution, large-aperture multidimensional arrays.

The report of the Panel on Technology, Volume 2 of the full nine-volume series *Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force*, describes the supporting computational and sensor component technologies that are expected to have a positive impact on technology development for ASW systems. The following technologies are unique to the Navy ASW mission and may require direct Navy support for their further development:

- Array technology
  - Low-cost horizontal, vertical, and multidimensional arrays with dense sensor spacing
  - Reliable array deployment and handling
  - Modular, fiber-optic data telemetry
- Environmental data acquisition
  - High-resolution environmental databases
  - Assimilation of real-time oceanography
  - Real-time satellite data
- Processing hardware and software
  - Modular, commercial off-the-shelf (COTS) systems with open architectures for rapid insertion of upgrades
  - Teraflop massively parallel processors and beam formers
  - Postprocessors for track and environmental management
  - Data management for networking processing and displays.

Countermeasures and Sonar

The emphasis in ASW has been on increasing detection gains faster than gains in quieting and stealth. In confrontational situations, ASW system performance can be affected significantly by aggressive techniques such as jamming and spoofing, which are more generally part of countermeasure technology. Anticipated gains in submarine quieting and increased use of off-board sensors, together with the cost and difficulty of increasing detection range, makes it prudent to increase the emphasis on ASW acoustic countermeasures and counter-countermeasures. ASW has not developed countermeasures and, subsequently, counter-countermeasures in any meaningful degree compared to those now routinely used in radar. ASW could certainly benefit by expropriating some of the radar countermeasure work. Countermeasures can be used to frustrate all aspects of ASW from initial acquisition to localization and, finally, targeting. High-gain processing exploiting coherence to its limits is very susceptible to jamming. Sensor networks have the same vulnerability to jamming of critical links or nodes. The acoustic environment is quite different from radar, and so the applicability of countermeasure technology has to be determined.

Sound Surveillance System

The SOSUS arrays have been the principal fixed arrays deployed over long periods. Although considerable research was done within the classified community, the data were not routinely accessible to the acoustics research community. Yet, addressing several of the imperatives for passive ASW that exploit fully coherent processing with large-aperture arrays requires a facility where these research issues can be addressed. Experiments with fixed arrays are necessary because towed arrays introduce both motion effects and positional variability, which complicate measurements and analysis. Over the years, several large arrays have been deployed for short durations for research purposes; a horizontal array buoyed up into the water column was deployed in the 1970s to examine coherence issues. The most recent notable example was a system of multiple, bottom-moored vertical arrays where matched-field processing was a focal point. Largely because of the expense and the complex ocean engineering required, there has never been a research facility with long-term observations addressing the ultimate ASW capabilities of passive sonars with fixed arrays.

This draws attention to the future of the existing SOSUS system. Although it is not an ideal facility and certainly not the one that is really needed to address the acoustic and signal processing issues outlined above, it does exist and thus constitutes an available source of at-sea data. The use of SOSUS for research has two aspects—one for ASW and a second for oceanography. Important ASW research issues for fixed systems can be addressed in the short term by augmenting SOSUS facilities, and possibly FDS and ADS, with vertical arrays having their own data telemetry; moreover, critical experiments can be done that can help to specify the configurations of future systems. The maintenance of some components of SOSUS should be addressed from a Navy perspective.

The scientific use of SOSUS has been an issue for the last several years because SOSUS represents an acoustic observatory system long sought by the research community. Acoustic observation of earthquakes and marine mammal activity and acoustic tomography are examples of the type of data that SOSUS can provide. The scientific use of SOSUS is compatible with the Navy's ASW needs because it can provide fundamental data on ambient noise sources and acoustic propagation. For example, sea organisms and microearthquakes are important VLF noise sources, and much of what has been learned recently about deep-ocean coherence came from SOSUS-acquired data. Although there have been financial issues that are important in today's tight budget climate, security has been the fundamental problem for general use of SOSUS by the scientific community. The acoustics community has long sought an acoustic observatory, and maintaining some parts of SOSUS represents the closest possibility. This issue warrants careful consideration in light of the potential long-term benefits to the Navy's ASW program.

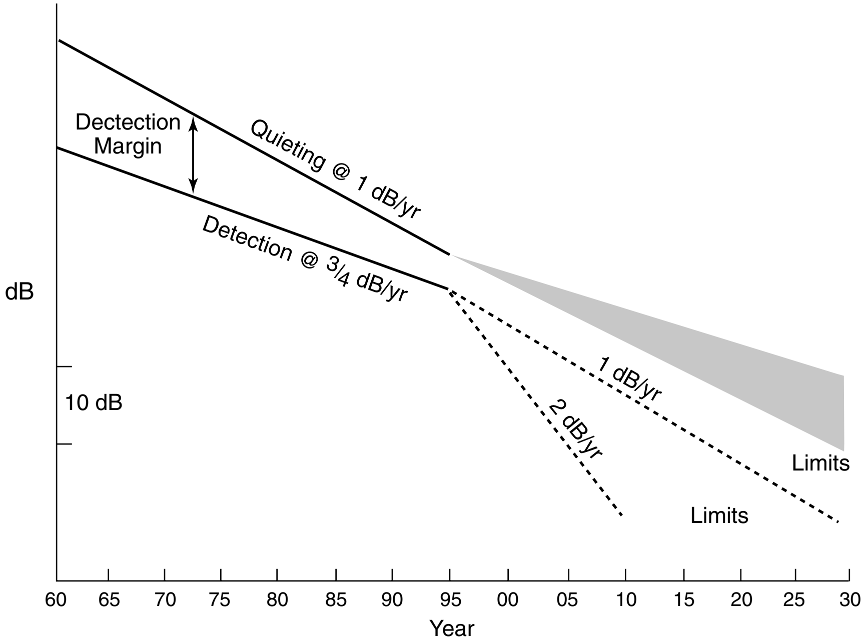

FIGURE 1.1 Trends and projections for submarine quieting and acoustic detection limits.

SIGNIFICANT GAINS POSSIBLE IN PASSIVE ACOUSTICS

The acoustic energy emitted by the world's first-line submarines, both nuclear and diesel and both narrow-band and wide-band, has decreased at a remarkably constant rate over the past 35 years—about 1 dB per year. This came about because of extensive and sophisticated quieting R&D programs involving submarine designers, component producers, and structural acoustics technologists. Despite the impressive 35 dB of quieting, even the best submarines operated properly at low speeds can still be detected—advances in passive acoustic detectability via improvements in sensors, arrays, and processing techniques have almost, but not quite, kept apace of the quieting. Nevertheless, passive detection ranges for these low-speed modern submarines have shrunk from hundreds of kilometers to only a few kilometers.

These trends, illustrated in Figure 1.1, if continued into the next 35 years will lead to essentially undetectable submarines and will reduce ASW capabilities to close-proximity detections and transient or higher-speed situations. However, the technologies are ripe for a sharp change in the slope of the detectability history curve—improvements averaging several decibels per year are on the horizon and could come to fruition with vigorous pursuit of the requisite R&D.

These new opportunities stem mainly from the advent of massive, affordable computational capabilities synergistic with new and affordable sensor developments and an improved understanding of what the ocean will permit by way of coherent and matched-field processing. It is time for the fulcrum of the lever to shift—to put detectability on the long end. Whereas future quieting will be difficult and will involve continued excruciating attention to detail and extensive testing, advances in detection capability, although not simple, can occur and be inserted on a much shorter time scale than has existed in the past.

The enabler is the now-occurring introduction of open-architecture, COTS-based systems in ASW platforms and acoustic processing chains. A sea change is taking place: special-purpose, MIL-spec hardware and software with decades-long life and replacement cycle times are being replaced with open-architecture, COTS component systems that allow hardware-software refresh times of a year or two. This approach is currently being implemented successfully in submarine combat systems and can, by logical extension, be applied to other ASW systems.

At the same time, relatively cheap but high-performance sensor and telemetry or connection concepts are maturing, based on fiber optics for both sensors and telemetry and MEMS or other miniaturized sensor concepts. These developments enable not only the processing of more signals with higher bandwidths from more sensor elements with ever more sophisticated algorithms, but also exploitation of the details of the local ocean environment through temporally and spatially coherent processing as well as spatial signal replica/adaptive beam forming—the so-called matched-field processing.

As arrays, both mobile and fixed, become larger in both number and length, engineering issues associated with handling and placement or control may become apparent. The oil industry has made major advances in deploying multiple towed arrays. The Navy should maximize the benefits of the experience and lessons learned in the oil exploration industry.

SIGNIFICANT POTENTIAL FOR ACTIVE ACOUSTICS

Active acoustics, although fielded as a Navy tactical capability for many years, has experienced significant advances over the past decade or so with the promise of much more improvement to come. Advances include the following:

- Exploitation of frequencies well below 1 kHz where reduced attenuation allows longer detection range, perhaps much longer ranges in deep water, compared to the higher-frequency (> 1 kHz) tactical sonars;
- Development of low-frequency sources with increasing power and efficiency, increasing bandwidths, and smaller sizes, all of which will allow an increasing variety of sources for future applications;
- Separation of transmitter(s) and receiver(s) into various distributed system configurations;

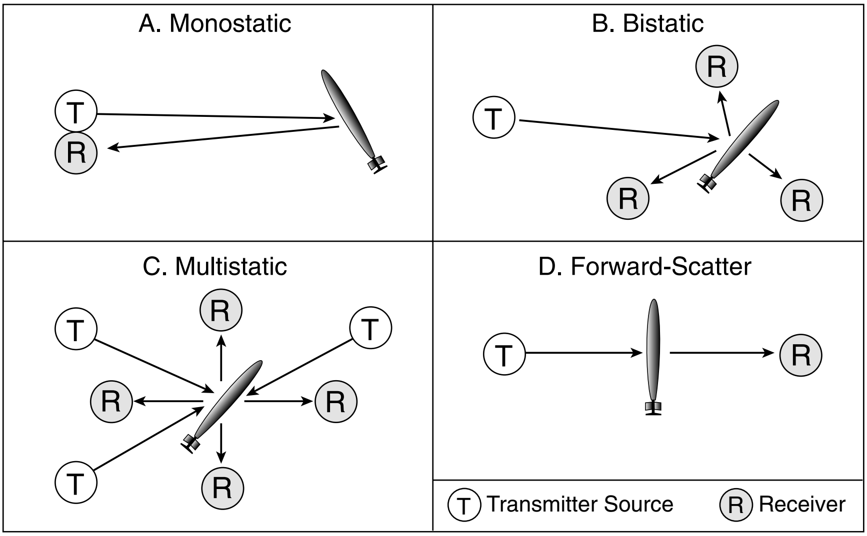

FIGURE 1.2 Basic transmitter and receiver configurations for four different active acoustic concepts: (A) monostatic, (B) bistatic, (C) multistatic, and (D) forward scatter.

- Varieties of waveforms, including wavetrains, wide bandwidths, and impulsive, combined range and Doppler sensitivities; and
- Advanced processing algorithms and techniques for clutter reduction.

In addition, receiver and processing advances in passive acoustics will directly benefit the active side as well.

Typical active acoustics system concepts are shown in Figure 1.2. Concept A represents the more traditional monostatic configuration common to all tactical sonars as well as the SURTASS-LFA system using the research ship *Cory Chouest*, now assigned to the Pacific fleet. Concept B has proven to be quite valuable in certain environments where surface ships, submarines, buoys, and fixed systems with bistatic receivers can provide detection capability at greater distances from the transmitters.

Concept C extends the bistatic concept to include multiple transmitters and, thus, can achieve significant area coverage by distributed fields of multiple transmitters and multiple receivers. The use of distributed sources and receivers greatly complicates the target submarine's ability to hide, evade, or attack and further ensures the safety of manned platforms when the sources (and perhaps receivers as well) are autonomous and separated from the manned platforms. Multiple sources prevent the target from avoiding Doppler or specular orientations while receiver locations can remain covert. Such configurations have been tested fairly extensively by the Navy and are also routinely used in offshore seismic oil and gas exploration.

Concept D represents an alternative detection concept to the monostatic, bistatic, or multistatic approaches, all of which are based on the backscatter of acoustic energy from targets. Forward scatter achieves detection only when the target crosses the line between source and receiver but has the advantages of significantly lower transmit power and increased difficulty for countermeasures by target strength reduction. Thus, fields of many low-power sources and receivers could provide a surveillance web tracking a submarine as it cuts across individual source-receiver lines.

Continuing advances in active acoustics, in both transmitter and receiver technologies, combined with advances in unmanned systems, computational power, and C^4ISR (command, control, communications, intelligence, surveillance, and reconnaissance), could lead to active system concepts that cover large areas at reasonable cost. Unmanned underwater vehicles (UUVs), unmanned aerial vehicles (UAVs), or unmanned surface vehicles (USVs) could deliver or act as transmitters or receivers. UAVs could also act as communications relays or weapon deliverers. Overall, active acoustics could confound an adversary without putting manned platforms at risk. Transmitter technology should continue to advance to provide lighter-weight sources with higher output power and more bandwidth. Autonomous sources and/or receivers will permit the continued development of concepts using fields of distributed sources and receivers to very large scales. Exact system configurations will depend strongly on the environment because it is critical to get acoustic energy on target and the reflected energy to a receiver.

A significant issue will continue to be clutter removal by advanced processing techniques. With numerous distributed receivers and accurate navigational capabilities (e.g., GPS) multisensor data processing concepts, either incoherent or perhaps coherent, could provide significant gains in target detection and classification.

A major concern for the testing and use of lower-frequency active acoustic concepts, particularly those involving backscatter, is the fear of physical harm to humans (divers) and marine animal life exposed to high acoustic signal levels (see Appendix D). Efforts are under way to establish safe levels for humans, particularly, but longer-term efforts to address the issue, including marine animal life, could lead to limitations on transmitter power, areas of operations, frequency, and so on. The conclusions of such research could affect the types of systems developed in the future. Because of the lower power requirements, multistatic backscatter and forward-scatter concepts may be preferred. The entire subject of what constitutes safe levels of active acoustic emissions in various situations should be addressed explicitly by the Navy. The Navy should become the recognized leader in establishing the knowledge base from which regulatory limits will be determined.

Overall, active acoustics has significant potential to provide a robust search capability in reasonably large areas, and although it is difficult to avoid counter-detection by an adversary submarine, the bistatic, multistatic, and forward-scatter concepts can mitigate most adversary countermeasure approaches. As with passive acoustics, none of these developments will occur without the dedicated, focused, long-term R&D projects based on extensive at-sea testing that have proven necessary to make real advances in detectability. Although COTS can provide the processing hardware, the submarine detection applications and systems remain unique to ASW, without counterparts in the commercial or, for that matter, other military endeavors. Because of advances in submarine quieting and the use of off-board sensors, detection ranges in some scenarios are beginning to fall into those commonly associated with modern mine-hunting sonars. As detection ranges decrease, the role of high-frequency sonar for both passive and active systems may become more prominent.

NONACOUSTIC ASW: A NEEDED COMPLEMENT TO ACOUSTICS

Based on the current technical understanding of nonacoustic submarine signatures and their detectability under various operational and environmental conditions, nonacoustic ASW concepts will, in general, complement acoustics in at least the following ways:

- Exploit shallow submarine operations, particularly when acoustic detection might be degraded, thus inhibiting an adversary from using an important part of his operating envelope and denying him a safe haven from acoustics.
- Exploit a submarine's hydrodynamic signature, which is unavoidable under many conditions when the submarine must move to conduct most missions.
- Contribute independently derived glimpses or moderate-quality data to the overall data fusion process.

Nonacoustics must be considered in the context of four target operational regimes:

1. Periscope depth with exposed masts or scopes,
2. Periscope depth with all masts or scopes retracted,
3. Nominal safe operating depth to avoid surface ships (roughly 150 feet), and
4. Lower depths down to design depth or on the bottom.

Current or developmental ASW capabilities exploit such regimes to varying degrees. For regime 1, sensors such as visual, low-light-level television (LLTV), periscope-detecting radar, and electronic support measures (ESMs) work when exposure occurs. Since exposure can be controlled to a few seconds, the glimpse-only scenario is viable for those sensors.

However, the submarine may stay at periscope depth conducting periodic exposures, thus making regime 2 also a viable scenario. Detections by magnetic anomaly detectors (MADs), infrared (IR) detectors, passive optics, and laser detection and ranging (LIDAR) are now possible for regimes 1 and 2. Under certain conditions, MAD and LIDAR may detect submarines in regime 3 and MAD could conceivably extend to regime 4.

Most current nonacoustic systems are deployed on fixed-wing aircraft or helicopters. ESM is on all platforms, while surface ships may have limited visual, IR, and radar capabilities.

The current U.S. technical knowledge base in nonacoustic ASW is fairly robust, with significant investment by the Navy in many programs and continuity residing currently in the SSBN Security Program. In addition, DARPA, the Central Intelligence Agency (CIA), and currently the Office of the Secretary of Defense (OSD) have projects that contribute as well to the knowledge base. For the long term, this knowledge base suggests areas of significant payoff:

- Evolutionary improvements in current capabilities that exploit shallow submarine operations (regimes 1 and 2) although some signatures such as periscope cross section, magnetic, and perhaps optic might be successfully reduced.
- Concepts that exploit the hydrodynamic signatures; hydrodynamic effects cannot be controlled to below detectability thresholds under many conditions. Such concepts can be categorized into three types:

1. Remote detection of surface effects by airborne or space-based sensors (e.g., synthetic aperture radar (SAR) IR, and optical);
2. Remote, but direct, detection of the submerged wakes or internal wave fields by airborne sensors (e.g., optics and electromagnetics); and
3. In situ detection of the turbulent wake, contaminants contained in the turbulent wake, or the internal wave field using sensors mounted on or towed from surface ships or submarines.

In addition, extension of the above concepts to space, unmanned air, and undersea vehicles could act as force multipliers for all sensor concepts. In general, nonacoustics is not a robust ASW solution but an opportunity-exploitable approach that inhibits or exploits important portions of an adversary submarine's operating envelope. However, there may well be situations, particularly in the littoral, in which search areas are not large and acoustic conditions are poor; therefore, nonacoustic sensors could become a significant ASW contributor.

UNMANNED UNDERWATER VEHICLE NETWORKS: A ROLE TO PLAY

One development currently in its infancy is the use of networked unmanned underwater vehicles[11] for synoptic (fully three-dimensional) environmental sensing. Such environmental information, obtained through local sampling or tomography, could be of significant operational usefulness in improving sonar capabilities. In addition, the imagination is stimulated by the vision that many small, dispersed platforms could be connected with a few manned platforms for networked warfighting. Such a vision is currently premature but might become practical over the time horizon of this study. The panel believes that the environmental sensing applications of UUV networks should be pursued first. In this way, the Navy will develop the enabling technologies for such networks, as well as operational experience in their deployment.

The two key enabling technologies for UUV networks are their power sources and reliable underwater communications. There has been much activity in the area of air-independent long-duration power sources, but there does not seem to be any consensus regarding which of many possible avenues—batteries, fuel cells, and air-independent combustion—should be pursued. This is an area in which considerable interest also exists in the commercial sector, and new long-duration power sources may arise from activities such as the Partnership for Next-Generation Vehicles. Thus, a top-down research approach may be effective in guiding R&D in this area into the most promising paths.

Currently, the leading candidate for underwater communication is acoustic communications. Data rates of 2 to 20 kilobits per second (kbps) are currently achievable, although distances are limited to a few kilometers in shallow water. It is even possible to give UUVs Internet addresses and to communicate with them using standard Transmission Control Protocol/Internet Protocol (TCP/IP) protocols. An improved understanding of ocean acoustic coherence, discussed elsewhere, could also improve our ability to communicate underwater. Little work, however, has been done on the vulnerability of acoustic communications networks to acoustic jamming or on covert underwater communication.

UNDERSEA WEAPONS—A FUTURE PERSPECTIVE

The continuing evolution of the potential submarine threats facing U.S. forces and the expanding set of roles and missions for Navy platforms, particularly submarines, require advancements in weapon capabilities for the future in order to counter the threat and to ensure success in the complex scenarios envisioned. At present, the Navy maintains an inventory of submarine-launched Mk-48 and

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[11] National Research Council. 1996. *Undersea Vehicles and National Needs*, National Academy Press, Washington, D.C.

Mk-48 ADCAP torpedoes and surface- or air-launched Mk-46 and Mk-50 torpedoes. Although important programs are under way to improve weapon capabilities such as the Mk-48 ADCAP modification and the lightweight hybrid (utilizing elements of the Mk-46 and Mk-50), these efforts can be viewed as minimally sustaining the R&D capabilities for undersea weapons. Concurrently, a drawdown of weapon inventories is under way.

In the near- to mid-term time frame, the focus will be on improving the performance of undersea weapons in complex, littoral environments and scenarios against an increasingly stealthy submarine target equipped with sophisticated countermeasure devices for thwarting a weapon attack. Insertion of new technology in signal processing, detection and classification, sensors, and guidance algorithms is planned. Design changes will be undertaken to achieve reduction of costs for weapon test exercises and life-cycle support. In the case of submarine-launched weapons, in particular, design changes that reduce the radiated noise signature of the weapon will reduce the counterdetection range by the target and the effectiveness of the target's counteraction. The current inventory of undersea weapons will be upgraded to utilize advances in electronics and computer technology to exploit very wide-band signal processing in order to enhance detection and homing against the low-signature threats employing multiple, complex countermeasure devices.

In the next 10 to 20 years, the current inventory of weapons will have to be replaced by weapons with significantly advanced capabilities. The advancements required will be driven by new approaches and scenarios for engaging the target submarine and by consideration of the platform design flexibility that new weapons can provide. One such scenario is a rapid attack situation wherein a sudden detection of a threat submarine is made, perhaps at relatively short range, requiring an immediate response to achieve weapon on target and, for of our own submarine, to ensure survival. Advances in hydrodynamics such as supercavitating flow coupled with new fuels that utilize seawater as an oxidizer will provide an option for very high speed weapons that may be employed to greatly shorten the time from weapon launch to target engagement or, conversely, from weapon detecion to response. For engagements at attack ranges similar to those of today, advances in power and energy density of undersea propulsion systems will provide the capability for reducing the size of weapons or increasing performance in terms of speed and range. Reduced weapon size, such as submarine-launched torpedoes that are one-half the current length with equivalent or better performance and payload effectiveness, would significantly increase the options available to submarine designers.

Although individual surface, air, and submarine ASW platforms must retain the capability to cope with the advancing threat, future ASW operations will likely evolve in a cooperative engagement sense that simultaneously utilizes the capabilities of multiple assets. In such a situation, the platform delivering the weapon may not be the same as that maintaining track on the target and generating a targeting solution. The inherent stealth of the threat submarine, projected to have even further signature reductions in the future, implies that a detection and ASW weapon targeting system will rely increasingly on distributed short-range sensors, glimpses of signals embedded in clutter, and extensive data fusion to function effectively. During hostilities, these occasional valid contacts would have to be exploited rapidly and accurately by a cooperative engagement, rapid attack weapon system. Such a weapon system would consist of a delivery capability to distances up to 10 to 20 nautical miles from the launch platform with a total response time of minutes, a reacquisition capability to locate and track the target within a relatively small area (a few miles radius), and a terminal attack weapon. The enabling technologies for such a concept might include the following:

- A high-bandwidth sensor data network and fusion capability (i.e., an undersea cooperative engagement capability [CEC]);
- A rapid-response, high-speed airborne delivery vehicle;
- A UAV with long loiter time carrying a shorter-range, high-speed delivery vehicle;
- Rapidly deployed distributed sensor field on datum with fused processing; or
- Off-board guidance and control of the weapon to the close-in vicinity of the target, potentially using a high-bandwidth data communication to the weapon that permits wide-band, intersensor processing between a weapon and off-board sensors.

Further, the possibility of weapon attacks from much longer standoff ranges is envisioned. To this end, weapons capable of long-endurance, stealthy closure of the target before the attack occurs would be needed. One such concept involves use of a UUV-like vehicle a weapon or a weapon delivery platform. Such a weapon would be capable of operating in concert with a distributed sensor field providing long-range target detection and vectoring to a position for launching an attack.

The proliferation of sophisticated undersea weapon systems available to potential adversaries will drive a concerted effort to achieve assured self-defense against incoming torpedoes for both surface ships and submarines. A major focus of this effort will be on counterweapons (i.e., hard-kill antitorpedo torpedo, capable of intercepting an incoming torpedo and destroying it). The technology of the future could permit a small counterweapon to autonomously detect an attacking torpedo, close on it at high speed, maneuver at high rates, achieve a relatively close point of approach, and fuse a lethal warhead to kill its target.

EXPANDING NEED FOR COMPREHENSIVE ASW CONCEPT OF OPERATIONS

ASW is often perceived as a submarine-versus-submarine problem. This has never been the only scenario and will be less so in the future. ASW has always been the integration of information from mobile and fixed assets; in the future, successful execution of undersea warfare will involve the fusion of data from multiple sensors—below the surface, above the surface, in the atmosphere, and ultimately, in space. These platforms will be fixed as well as moving, surfaced and submerged, flying, and orbiting.

The potential of space-based sensors has not been realized. Sensing the various hydrodynamic effects created by a submerged hull moving through the ocean may be possible with key enabling technologies yet to be fully exploited. Future space-based sensors, whether they be developed for environmental information or for military applications, will provide additional information to be fused into a complete picture of the ASW situation.

Modern maritime helicopters have proven to be extremely effective ASW vehicles. Their capabilities and strengths derive from the ability to operate from small platforms at sea and use deployed and on-board sensors, including dipping sonars, to prosecute submarine contacts. Speed, range, and endurance are the most limiting factors of current ASW helicopters. New vertical takeoff and landing (VTOL) aircraft, with capabilities at least equal to the tilt rotor V-22, hold promise of overcoming these limitations. There is no question about the desirability of a VTOL aircraft that could proceed at 250+ knots to a distant (200+ nautical miles) contact area and prosecute a submarine target with time on-station and effectiveness equal to or greater than those of the SH-60R at its normally shorter operating ranges.

Technology advances in unmanned systems will allow the proliferation of sensors over the undersea battle space without exposing manned platforms to unacceptable risks. Unmanned air, surface, subsurface, drifting, and fixed platforms will act as force multipliers to provide a highly integrated network to address the ASW problem. These same technology advances will also provide a threat multiplier for potential adversaries.

The increasing complexity of future ASW concepts of operations and the need to test them in an even more complex joint arena require that modeling and simulation become a significant facet of ASW systems development, training, and decision aids. The difficulty will remain the existence of validated models that faithfully characterize the physical processes associated with the generation, propagation, and detection of acoustic or nonacoustic signals in a wide range of environments, some of which are quite complex and harsh. Although the best possible models of appropriate fidelity should be employed in large-scale and joint simulations, it is important to maintain a strong focus on the R&D necessary to understand and maximize the detection processes, which in turn will result in improved, if not validated, models for use in simulations.

The successful Navy of the future will be the one that assimilates disparate data into a meaningful integrated whole. Technologies such as GPS enable sensors at widely spaced locations to be combined as though they were close or fixed on the same platform. Communications capability using high-bandwidth fiber-optic cable and satellites is exploding, driven by the information and communications industry. In addition, special communications based on acoustic and blue-green laser technologies are possible to enhance the connectivity of underwater systems. Leveraging these capabilities puts ASW on the threshold of a major transition. The potential to process raw sensor data, either incoherently or coherently, from a field of sensors of various types is now conceivable, given emerging technologies. Thus, a concept analogous to the CEC of the air defense warfare domain can now be envisioned for ASW. For ASW CEC to be carried out effectively, it must incorporate assets of multiple platforms, technologies, and information sources. This level of cross-platform, cross-disciplinary cooperative engagement will require high-level, authoritative coordination.

RESEARCH OPPORTUNITIES

Emerging enabling technologies will make currently unachievable system concepts realizable in the coming decades. Examples of these concepts with their requisite enabling technologies are presented in Table 1.2. It is evident that the

TABLE 1.2 Possible Future ASW Concepts

Concept	Enabling Technologies
Submarine detection, instant localization from space or air vehicles	Many decibels of clutter rejection in SAR, optics
Hull	High-resolution, multipixel focal arrays (visible, IR)
Wake	
Surface effects	New blue-green laser concepts
Picobuoys (highly distributed floating sensors)	Small, cheap sensors with navigation, communications, processing
Portable phase conjugate systems for self-adaptive, autofocusing active sonar	Lightweight transmitters; computational capability
High-power, efficient, small, high-bandwidth acoustic sources	New transmitter concepts, materials
Coherent sensor fusion: acoustics, electromagnetic, optics	Ultrahigh digitization rate technology
Undersea acoustic systems for localization, navigation, and adaptive focusing	Network and source technologies

research technologies associated with information processing and sensors, much of which are being developed independent of Navy requirements, are the key to realizing these system concepts. These technologies represent a research opportunity for radically enhanced ASW capabilities.

RECOMMENDATIONS

While ASW remains a technically challenging warfare area, there are a number of steps the Navy can take to remain in control of the undersea battle space into the next decades.

Highest-level Recommendations

- Establish and maintain a dedicated long-term program, centered on at-sea measurements and tests, to provide the science and technology bases for pushing active and passive acoustic array gain to the limits imposed by the ocean. Decades of experience have shown that advances in ASW come about only as a result of such programs.
- Focus passive and active ASW sonar development on exploitation of the ocean's intrinsic coherence and on the use of large volumetric arrays, as enabled by massive computational power, miniaturized sensors, and high-bandwidth transmission links, with a goal of 20-dB or greater detectability gains beyond near-term programmed improvements.
- Develop networked, distributed sensor fields, including unmanned platforms (e.g., UUVs, UAVs, and satellites), for both submarine detection and local environmental characterization.
- Develop weapon concepts and technologies that will exploit distributed sensor networks, permit rapid response, and provide more capability against countermeasure-equipped quiet submarines and torpedoes.

Recommendations for Follow-on Action

- Elevate and maintain the priority for ASW R&D within the Department of the Navy to ensure capabilities to counter the future submarine threat.
- Determine the limits of acoustic concepts such as coherent and matched-field processing with volumetric (both horizontal and vertical) arrays through comprehensive environmental measurements, accompanied by modeling and testing.
- Use SOSUS data to explore ocean coherence and other acoustic phenomena that will be fundamental to the next generation of sonar technology.
- Incorporate engineering experience connected with the manufacture and deployment of large towed arrays gained by the offshore oil exploration industry.

- Develop power supplies and other key enablers for autonomous deployable low-frequency acoustic sources.
- Quantify the operational, algorithmic, and communications requirements for distributed active sonar methods including bistatic, multistatic, and forward-scattering configurations.
- Ensure that the Navy is the leader in understanding the environmental impact of acoustic energy on mammals and other marine life.
- Establish and implement a road map to exploit miniature sensor developments for undersea applications, including microelectromechanical systems technology, both inside and outside the Navy.
- Continue to pursue promising nonacoustic ASW detection techniques, including magnetic, electro-optical, and biological.
- Establish an ASW research program to exploit the effects of submarine hydrodynamic signatures, especially in littoral environments.
- Improve the capability of ASW weapons against stealthy submarines operating in littoral environments and deploying complex countermeasures, including the exploitation of advanced sensors, expanded processing bandwidths, and environmental adaptability.
- Develop technologies that will enable a family of new weapon concepts such as rapid attack, long-range response to off-board sensing and targeting; short-range, close-in, quick reaction; and long-endurance, stealthy UUV-like search-track-kill weapons.
- Pursue robust enabling technology for protecting surface ships and submarines against threat torpedoes, such as antitorpedo weapons and advanced countermeasure devices.
- Adopt open-architecture and COTS-based systems in all ASW applications to enable hardware or software refresh cycles of approximately two years.
- With the aid of GPS, build on the capability to network widely spaced platforms, such as UUVs, and large distributed acoustic arrays and satellites, to provide data, including environmental information, that can be fused into a complete ASW picture.
- Adapt improved technology VTOL aircraft for ASW to provide greater range, speed, and endurance capabilities than current helicopters.
- Ensure a continuum of robust fleet ASW R&D projects characterized by at-sea operations, testing, measurements, and experimentation as the principal means of advancing the slate of future fleet ASW capabilities and readiness.

The panel is fully confident that taking advantage of the opportunities to incorporate available and emerging technology will enable the Navy to maintain undersea superiority well into the next century.

2

Mine Warfare

The post-Cold War environment and the disappearance of the Soviet naval threat have reduced the Navy's focus on the blue waters of the open ocean and instead concentrated its attention on the littorals of the world. During the Cold War, the Navy was sized and configured to engage the Soviet fleet and its land-based naval air. Focused attention on the Soviet blue water threat resulted in comparative neglect of the unique requirements of operations in close proximity to land. As an aside, it is ironic that the Navy-Marine Corps team actually fought all its wars during that period—Korea, Vietnam, Grenada, Persian Gulf—in the littoral regions.

Today and for the foreseeable future, the nation will require a Navy different from the one that was developed to counter the Soviet threat. The phrase, "we will never again be faced with an opposed amphibious assault," first articulated in the 1960s, is heard no more. The panel foresees an increasing number of instances where the Navy and Marine Corps will be required to operate freely in near-shore waters, and the forces at their disposal, including MCM forces, should be configured such that they are able to operate effectively in these environments. At the same time, during the projection period of this study (2000-2035), a blue water threat may again emerge. Thus, the Navy of the future will require a balanced capability that can sustain operations in both the blue water and the littoral environments.

The experiences of Wonsan in the Korean conflict and Kuwait in the Persian Gulf War indicate that sea mines, in the hands of a far lesser power that knows little of how to use them, can defeat, at least temporarily, the most powerful navy in the world. Today at least 45 countries, in addition to the United States and the former Soviet states, possess mining capability, and any nation can acquire such a capability in a matter of months. At least 21 countries are known to produce mines, and 13 are confirmed mine exporters. The People's Republic of China, for instance, has sold copies of Russia's AMD/KMD II bottom influence mines in both the 500- and 1,000-kg versions and has marketed its own rocket-propelled mine, the EM52, designed to be deployed in relatively deep water against both submarines and surface ships. Yugoslavia produces mines based on Russian designs. Italy produces the Manta and computer-controlled MP-80 influence mines. It was a Manta mine laid in about 60 feet of water that seriously damaged the hull of the USS *Princeton* (CG-59) during the Persian Gulf War and disabled its Aegis antiair combat system and vertical launch system (VLS) missile batteries. Chile offers three mines for sale, including a microprocessor-controlled magnetic influence mine, the MS-L, and a version targeted at landing craft, the MS-C. Unfortunately, the known 45 producers of mines do not, in themselves, define the threat since virtually any country can produce an effective mine. It was the LUGM-145 moored contact mine produced by Iraq that damaged the USS *Tripoli* (LPH-10) during the Persian Gulf War. Further, mines do not have to be of modern design to pose an effective threat to naval operations. The mines used by Iran during Operation Ernest Will were from the Russo-Japanese War (1904-1905) with two upgrades. Many of the Turkish mines in the Dardanelles that forever changed world history during the Gallipoli campaign of World War I were Russian mines that floated through the Bosporus and were salvaged, refurbished, and replanted.

Although mines can be cheap and simple, countering mines will most probably become more difficult due to increasingly sophisticated fusing methods and the ease with which mine signatures can be reduced. Miniature solid-state firing mechanisms and logic processors will allow increasingly complex acoustic-, magnetic-, and pressure-triggered mines that will evade existing sweeping techniques. Mines with reduced acoustic signatures will seriously degrade the performance of mine hunting sonars. The plastic-hulled Manta and the wedge-shaped Swedish Rockan GMI-100 are current examples of reduced signature mines that are believed to be difficult to detect. It is not unreasonable to expect to encounter mine systems that use distributed sensors and remote command and control (RECO) activation or deactivation through acoustic or electromagnetic links.

During the past 45 years, in spite of the very modest effort devoted to mine design the explosive charge carried by the typical mine has essentially doubled in energy output; its instrument section has been reduced from 20 percent of its volume to a space the size of a soda can through the adoption of modern electronics; its lethality range has increased from a few tens of feet athwart ship to a half mile through the use of mobile warheads; its logic systems have been made more resistant to countermeasures; and through the use of stealth technology, its ability to evade mine hunting sonars has increased. Future naval forces will be confronted with more capable mines made possible by evolving technology.

Prominent among the mine designs likely to be encountered between now and the year 2035 are (1) the self-burying mine, which would so degrade the performance of current mine hunting sonars as to force increased dependence on slower mine sweeping techniques; (2) another doubling of the warhead's energy output and continued reduction of the instrument section, thus increasing the delivery capacity of all mine laying platforms; (3) the introduction of alternating magnetic (AM), underwater electric potential (UEP), and possibly, pure pressure mine sensors; (4) the introduction of distributed sensor minefields in which the long-range multiple-shot kill component is located at a single point within or about the field; (5) mines specifically targeted against mine countermeasures (MCM) platforms, including helicopters; (6) the use of powerful minicomputers to increase the mine's target discrimination and resistance to countermeasures; and (7) whole minefields capable of remote command-on and command-off control and of changing sensitivity settings, sensor combinations, countermeasures logic, and even location on remote command. None of the possible advances enumerated above are particularly new, and all are within the reach of current technology. New technology developments will enable the design and fabrication of even more capable mines.

The Panel on Undersea Warfare chose to utilize the classified Naval Studies Board report *Mine Countermeasures Technology*[1] as starting point for its examination of mine warfare technology. The panel also took account of the 1995 White Paper issued by the Chief of Naval Operations[2] calling for a major sea change in the Navy's approach to MCM operations. Specifically, Admiral Boorda directed that the Navy's MCM force be transformed from a dedicated on-call force to an organic force capable of traveling at battle group speeds, and that MCM be mainstreamed into the fleet as a professional competency at all ranks and rates.

The panel's deliberations were guided by a view of MCM capability that enables effective pursuit of the following three objectives: (1) reduce the mine threat to its absolute minimum at each phase of an operation; (2) obtain maximum leverage of all available MCM assets; and (3) reduce the size and weight of all MCM systems without sacrificing capability. The panel believes that these objectives can be achieved and that a balanced MCM force, organic to the fleet and capable of removing the mine threat in keeping with an assault timetable or power projection schedule, can be achieved at relatively modest cost by the year 2005. Further, the panel has identified technologies whose far-term development would provide the Navy and Marine Corps team with an effective MCM capability well into the mid-21st century.

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[1] Naval Studies Board. 1992-1993. *Mine Countermeasures Technology*, Vol. I-IV, National Academy Press, Washington, D.C.

[2] Boorda, J.M., ADM, USN. 1995. "Mine Countermeasures—An Integral Part of Our Strategy and Our Forces," White Paper, Office of the Chief of Naval Operations, Washington, D.C., December.

The mine threat is expected to grow in technical sophistication over the projection period of this study; there is a substantial likelihood that mines will be developed that are difficult to detect and/or sweep. To deal with this issue, and more immediately with the threat of high-density minefields in the surf zone and on the beach, the panel addressed a number of so-called brute force technologies that deal with groups of mines, rather than single mines and obstacles, and do not depend on specific mine characteristics such as acoustic or magnetic signature, the type of fuse employed, or details of how the mine is deployed.

The panel restricted its consideration mainly to sea mines and to mines and obstacles found in the surf zone and the craft landing zone.

MINE COUNTERMEASURES: A VITAL CAPABILITY FOR FUTURE NAVAL MISSIONS

The Navy of the future will be expected to maintain sea control; to transit and operate worldwide at will; to navigate restricted waters, open channels, and sea lanes; and to project power ashore. It will be expected to land forces, supplies, and equipment rapidly and safely to support national objectives. Unless properly countered, mines will restrict, if not prevent, the Navy from carrying out these missions.

Technology in mine and countermine warfare in the next 30 years will be different than in the past because of (1) replacement of the Cold War preoccupation with port breakout, with the need for power projection into newer, troubled areas, which entails the protection of far-flung battle groups against mines, the clearance of shipping lanes, and in extreme cases, amphibious assault; (2) present and future reductions in defense budgets, which require that goals be pursued in the most cost-effective manner; and (3) the need to carefully integrate political and humanitarian with military imperatives, such as weapon choice, in the context of global peace.

Changes are required to meet the new missions and rules of engagement. Battle groups can no longer rely on a dedicated MCM force to provide protection against mines everywhere and anywhere. Each battle group must assume responsibility for self-protection against the mine threat with new organic MCM capabilities. The present, dedicated, MCM force must be reconfigured for worldwide operations. Mines are cost-effective weapons that can serve as an important force multiplier, but humanitarian and political considerations mandate that they not be deployed without sufficient control to ensure the limitation of collateral damage and injuries to third parties.

A VISION OF FUTURE MCM FORCES

It is anticipated that future battle groups will have organic MCM capability in the form of air, surface, and underwater platforms. The air platforms will likely be helicopters with improved, lighter MCM sonars, LIDAR devices, and possibly supercavitating projectile mine killers. The surface platforms will likely include remotely controlled, unmanned, small, stable, long-endurance platforms, possibly based on small waterplane twin hull (SWATH) technology, towing sonars and other MCM devices. Underwater platforms will include swim-ahead UUVs with mine detection, classification, and neutralization capability. The MCM force of the future will likely be composed of smaller and more numerous vessels, transported by a mother ship, that can be rapidly deployed worldwide to keep shipping lanes open and harbors cleared. Such a force will be designed to counter an arsenal of new mines with remote control, networking, and selective targeting capability.

It is unlikely that a single technology or system will emerge that alone will render the mine threat harmless. It is expected that future mine countermeasures will continue to consist of a number of systems ranging from the elemental to the highly sophisticated, each essential to a balanced capability to deal with the overall mine threat.

Five main thrust areas must be pursued in order to meet the MCM challenge of the future:

1. Robust intelligence, surveillance, and reconnaissance capability.
2. Integration of MCM as a capability organic to the battle force. This includes specific MCM capability resident on selected battle group combatants and expanded MCM capabilities provided by MCM ships and helicopters that are transported with the battle group or the amphibious ready group (ARG).
3. Technologies that address primarily the very hostile mine detection and neutralization environment of the surf zone and the craft landing zone. These generally fall into the brute force category.
4. Advanced networked sensor and weapon systems consisting of controllable mines and including autonomous and semiautonomous detection devices.
5. Application of cost-effective mine shock hardening and acoustic and magnetic signature reduction technologies in all new construction ships.

The following paragraphs expand on these thrusts.

Intelligence, Surveillance, and Reconnaissance

Accurate and complete intelligence, surveillance, and reconnaissance is the most effective means of enhancing the capability of MCM forces. ISR enhances the efficiency of MCM operations by reducing the threat to a minimum prior to the initiation of sweeping, hunting, and neutralization activities. ISR was the highest-priority recommendation of the Naval Studies Board report *Mine Countermeasures Technology*.[3] The importance and priority of that recommendation are reinforced and restated by the present study.

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[3] Naval Studies Board. 1992-1993. *Mine Countermeasures Technology*, Vol. I-IV, National Academy Press, Washington, D.C.

The recent increased attention to surveillance through such programs as the Radiant Clear Program, which seeks to develop a capability for littoral remote sensing, and the emphasis on reconnaissance-related research and development signal a possible turning point that, if pursued further, could provide the quality of intelligence that will become an effective force multiplier. It is to be emphasized that for this gain to be realized, priorities on the use of surveillance assets must be set now and the infrastructure installed for collection, analysis, and timely display of the resulting information. Intelligence requirements include a comprehensive database of world mines describing capabilities and characteristics, detection and triggering technologies, size and locations of stockpiles, manufacturing facilities, transportation routes, mine laying facilities and capabilities, and likely areas of deployment. Further, foreign manufacture and sale should be monitored, much like what is now done with respect to submarines. A robust ISR effort should include the acquisition and examination of foreign mines. This is a relatively inexpensive effort that holds promise for significant payoff, but one that has been poorly pursued in the past.

An effective factory-to-seabed ISR system should include a full set of ISR methods, including surveillance by satellite, atmospheric manned and unmanned vehicles, submarines, human intelligence, and special forces. Such a system would enable the preparation of detailed a priori plans and provide real-time support for the movement of forces. Ultimately, it could provide the option of interdicting mines prior to planting, or avoiding mined areas entirely, or failing both, it will allow MCM forces to be concentrated on mined areas of known characteristics.

Battle Group and Task Force Organic MCM

In a future where conflicts are likely to arise suddenly and unexpectedly, it will be necessary for naval forces to be capable of reacting swiftly and independently. Since the geographical locales of possible conflict are so widely dispersed, it will be impractical to create forward-based MCM forces. Thus, the dedicated MCM force the Navy has now must be transformed into a set of MCM assets carried by, or organic to, battle groups and task forces. The latter will be required to provide self-protection and deliver MCM capabilities to theater along with Navy presence.

A battle group MCM force might consist of a specially configured support ship with MCM command and control capability (C^4I), and the ability to transport and maintain small MCM ships and helicopters. MCM C^4I capability should include links to other task force elements, access to environmental sensors, including those deployed on satellites, as well as other data sources and decision aids to support tactical MCM. Provision should be made for special signals such as those required to implement remote mine neutralization on command. New hull concepts permit the design of smaller vessels capable of operating effec-

TABLE 2.1 Notional Small MCM Vessel and Support Ship

Small MCM Ship Design	Possible Sensors	Support Ship Characteristics
Length: 36 feet	Forward looking, low-grazing-angle LIDAR and sonar	Size: up to LSD dimensions
Displacement: 26 tons	Expendable mine neutralization	Payload up to 2-10 MCM ships 2-10 MCM helicopters
Payload: 4 tons	GPS navigation	JMCIS compatible
Low signature	Remote optical system	Battle group speed: 28 knots
24 knots	VDS sonar	Number: as appropriate for size and operational concept
Gas turbine/electric drive	Acoustic pulse power	
Active EM cancellation	Laser line scanner	
SWATH hull design	C^2-RF/fiber	
Sea state 4 capable	Optic, mammal, bioacoustic adjunct	
Modular (to allow air transport)	Deployable UUV	
Unmanned		
100 n. mi. endurance		

tively in sea state 4 conditions, and advances in lightweight sonars, synthetic aperture techniques, and lighter sweep gear will enable these smaller vessels to provide the functional capability of today's larger ships. Table 2.1 outlines a possible design.

Technology currently under development or likely to become available in the near future will allow battle groups to carry light helicopters that are capable of night operations and able to carry modular payloads including advanced electro-optic mine hunting systems, lightweight acoustic and mechanical sweeps, and mine neutralizers launched directly from the helicopter, such as gun-fired high-speed supercavitating projectiles. These will be augmented by off-board, remotely controlled, autonomous or semi-autonomous vehicles, with acoustic and other sensors and systems for mine detection, classification, and neutralization and with the endurance and ability to search ahead of the battle group at moderate transit speeds up to 15 knots. Undersea variants will provide covert reconnaissance capabilities.

Brute Force Mine and Obstacle Clearance

There will be situations in which MCM operations that deal with one mine at a time cannot be conducted because of the density of the threat and lack of time or because normal MCM operations are slowed or ineffective due to the harshness of the environment, stealthiness of mines, or presence of buried mines. In these cases brute force methods of breaching will be required. This is likely to be especially true in the surf zone (SZ), the craft landing zone (CLZ), and the beach regions—where a dramatic increase in the density of mines and obstacles may be expected. Brute force breaching methods may require complex engineering, precise timing and fusing of explosives, unique chemical systems, accurate navigation, and high reliability. There are two promising approaches that warrant further development: (1) precise time-space control of explosives that will remove mines and obstacles, and (2) the placement of a foam causeway over a mine field.

The Naval Studies Board *Mine Countermeasures Technology*[4] study recommended a concept in which precisely positioned (to GPS-level accuracy), impact-buried bomb explosives timed to go off nearly simultaneously, forming an equivalent buried line charge, are used to excavate a channel through the SZ, the CLZ, and through the minefield up the beach. See Appendix F for an explanation of the efficacy of simultaneous detonation for explosive channel excavation. Mines and obstacles are effectively removed from the deepened channel, which eventually fills with water, by the excavation process. The phenomenology, scaled dimensions, and removal of mines and obstacles have been confirmed by a scaled experiment conducted jointly at the UK Weston Supermare Shallow Water Test Range by the Naval Surface Warfare Center (NSWC) at White Oak, Maryland (now NSWC at Indian Head, Maryland).[5]

Independently, the Lawrence Livermore National Laboratory's (LLNL's) Defense Studies Group has proposed similar concepts using bombs available from inventory, with special fusing. Results of the NSWC experiment are in agreement with calculations performed by NSWC and LLNL.

If, as discussed in *Volume 5: Weapons* of this series, advanced explosives could be successfully developed in the 2000-2035 time frame, with several times current explosive fill effectiveness, a wider range of options for delivery and use of controlled space-time explosive patterns might become possible. The panel recommends that investigations and appropriately scaled experiments continue on channel excavation phenomenology and explosive placement sensitivity. Some of the needed data can probably be obtained using high-*g* centrifuges. An overall modeling capability should be achievable to enable tradeoffs of explosive weight, spacing, penetration depth, and channel width for different delivery and fusing options, threats, and environmental conditions.

Research conducted at Sandia National Laboratories on petrochemical-based binary materials has led to the development of quick-setting rigid polyurethane foam (RPF). The chemicals, transportable as liquids, when mixed and exposed to air form a relatively tough, quick-setting rigid structure that floats on the surface. The volume expansion between the component liquids and the final rigid foam is

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[4] Naval Studies Board. 1992-1993. *Mine Countermeasures Technology,* Vol. I-IV, National Academy Press, Washington, D.C.

[5] Furr, W., R. McKeown, and L. Taylor. 1996. "Mine and Obstacle Breaching by Explosive Evacuation in the Surf and Beach Zones," Technology and the Mine Problem Symposium, Monterey, Calif., November 18-21.

a factor of 20 to 60, and the resulting structure has a bearing strength sufficient to withstand the repeated passage of heavy vehicles, including tanks. Tests indicate that the foam can absorb some degree of explosive blast energy, can withstand puncture by bullets without significant structural weakening, and poses no extraordinary fire hazard. Tests also indicate that foam will incapacitate the sensors on pressure and tilt-wand mines if they are immobilized in the foam, will provide a standoff for magnetic mines, and will reduce the profile presented by obstacles to assault traffic. As important as these results are, more experimentation under actual operational conditions is needed to fully evaluate the potential of foam.

Other brute force systems offer promise and may be worthy of further development. Some concepts such as guinea pig ships and barges have been used operationally in the past, for example, in Haiphong harbor, during the Vietnam conflict. In this case, the ship was not employed as a sweep platform, although it was designed as one, but rather was used to prove that the United States had indeed cleared the harbor of mines. The same concept with improved automation, remotely controlled unmanned platforms, and precise navigation remains an attractive a means to prove that a safe passage has been cleared through a minefield.

Autonomous Networked Undersea Systems

Advances in sensors, signal processing, and computational power will enable the development of autonomous and semiautonomous systems. In support of ISR, networked multiple undersea surveillance systems using small, autonomous undersea vehicles have significant potential for providing a covert mine surveillance, detection, and neutralization capability. These systems could be smart systems, with a hierarchy of intelligence and capability, intervehicle communications within the water column, and communications to remote command and control nodes. They could operate autonomously, reporting only when interrogated or as programmed. The development of communications technology, acoustic and otherwise, will be an essential enabler for this type of system. Data transfer rates beyond those now possible will be required. Accurate navigation also will be required. Additionally, autonomous vehicle systems could be combined with other distributed sensor systems deployed either simultaneously or in sequence.

Vehicle technology pursued in past UUV research programs forms the basis for future efforts. Multiple vehicle approaches, which offer the efficiency of systems operating in parallel, could include stealthy surface vehicles and bottom crawling devices. Specific requirements, concepts of integrated operations, and possible countermeasures must be investigated, however, to more clearly define the viability of any single design. Such a system can be a force multiplier capable of detecting, classifying, and neutralizing mines either as a stand-alone system or incorporated as an integral part of a larger networked system. On the offensive side, the same technology can enable the development of networked autonomous weapons, including mines and minefields, with fail-safe remote control and command links and selective targeting. Such an offensive system can be a force multiplier by denying large areas of the ocean to enemy vessels without posing any danger to friendly forces and noncombatants and without tying up valuable Navy ships or putting personnel in harm's way.

Magnetic and Acoustic Signature Reduction and Platform Shock Hardening

Mine fuses rely on sensing the magnetic and acoustic signatures of ships and submarines for detection, classification, and initiation of their attack mechanism. Expected technology advances in mine fuses will yield improved sensitivity and noise rejection. Unless a commensurate effort is made to reduce the signatures of current and future platforms, their vulnerability to mines will increase in the future. Signature reduction measures that utilize both passive and active signature reduction techniques can be developed and implemented. Enabling technologies include sound- and vibration-absorbing materials and isolation techniques, active vibration and acoustic signature control, closed-loop adaptive magnetic degaussing systems, and cathodic current reduction.

Even with the most aggressive campaign to reduce signatures, there remains the possibility of triggering a mine. Indeed, a simple contact mine is not impaired by target signature reduction. Given this situation, especially as organic concepts of MCM are implemented wherein more ships will be placed in the vicinity of mines and minefields, it is essential that these platforms be shock resistant.

EMERGING ENABLING TECHNOLOGIES

Although the priority areas cited above will form a foundation for a robust future MCM capability, they must be bolstered by continued support for research in promising emerging technologies. The capability that the Navy is able to field in the future depends on research undertaken today. None of the required systems or technologies will be developed without a strong underlying R&D program. Lighter-weight sweeps with wider-swath, higher-resolution sonars; synthetic aperture sonars; active (laser) and passive optical systems; expendable neutralization methods; sonars based on biosonars (mammals) capable of detecting buried mines; and pulsed-power devices and biosensors will not be realized without a commitment to R&D. UUVs with intelligent control, long range, and endurance; networked underwater sensors; rigid foam causeways; small and stable surface platforms; and high-data-rate acoustic communications will not emerge without concomitant research. Optimum employment of systems and sensors based on the characteristics of the highly variable littoral environment will not occur without ocean physics, sedimentology, and meteorological research. The full benefits of modeling and simulation in the design of sensors and systems and in developing the most effective operational employment of the full spectrum of MCM capabilities will not be realized without an underlying research base.

TOWARD A BALANCED MCM FORCE: THE NEAR TERM

On the path to the MCM capabilities of 2035, the panel believes that the near-term concepts, technologies, and systems should, when integrated with existing capability, provide the Navy-Marine Corps team with the ability to clear mines in stride by the year 2005 or earlier, at reasonable cost. The panel kept several objectives in mind when evaluating these concepts and technologies. The first objective is to pare the mine threat in a given campaign to the minimum that must be dealt with effectively as a function of three phases of the campaign—the most critical phase in which the first forces are inserted, the second phase when the heavy manpower and logistics must be landed, and the third phase when maximum sea-based traffic is expected. From the MCM standpoint, the major distinction between the phases involves the channel widths to be cleared and the time to do so. The second objective is to achieve a balanced and flexible MCM system capable of countering the full spectrum of mine threats. The third and final objective is to select concepts that will add clearance speed and efficiency to the MCM system at minimal costs and that can be implemented in the near-term future.

Intelligence, Surveillance, and Reconnaissance

Intelligence, surveillance, and reconnaissance, considered as a whole, was the highest-priority recommendation of the Naval Studies Board *Mine Countermeasures Technology* report.[6] A continuous, robust ISR effort targeted at potential mine threats can greatly enhance the efficiency of MCM operations by enabling accurate characterization of the threat prior to initiation of sweeping, hunting, and neutralization activities. Many of the assets necessary for the intelligence and surveillance functions already are in place, and much of the technology development necessary for the reconnaissance function has been, and will continue to be, supported by entities other than the Navy.

Intelligence can provide information on the type, size, and location of an adversary's mine stockpile, the method and route of transportation to mine layers, platforms allocated to mine laying duty, and the adversary's plans for mine defenses. Surveillance by satellite, manned and unmanned aerial vehicles, submarines, human intelligence, and special forces can track mine laying activity from bunker to beach or sea bottom. Reconnaissance, preferably covert, by

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[6] Naval Studies Board. 1992-1993. *Mine Countermeasures Technology*, Vol. I-IV, National Academy Press, Washington, D.C.

airborne, surface, and subsurface sensors including mammals can provide ground truth to corroborate intelligence and surveillance information. Integrating ISR into MCM operations may allow the interdiction of mines prior to planting (rules of engagement permitting) or the avoidance of a mined area entirely; failing both, it should allow MCM forces to be concentrated solely on mined areas of reasonably well-known characteristics.

A number of surveillance assets, including electronic intelligence, satellite-based photo-optic cameras and sensors, manned and unmanned surveillance aircraft, Joint Surveillance and Target Attack Radar System (JSTARS),[7] submarines, special forces, and human intelligence can be used. The greater need is to set firm priorities for the tasking of these assets and to develop the architecture and infrastructure necessary for the mine warfare commander to receive the assembled data properly formatted and in a timely fashion.

The panel notes that the use of submarine mine layers represents a possible weak link in surveillance provided by the sensors and platforms noted above. Because of the proliferation and increased capabilities of submarines worldwide, with the capability of laying mines included, the panel believes that this weak link should be strengthened. The Office of Naval Research (ONR) and the Naval Research and Development Division (NRaD) at the Naval Command, Control, and Ocean Surveillance Center (NCCOSC) are supporting the development of remote sensors capable of detecting mine laying activity in waters seaward of the surf zone (ONR program) and both on land and in water (NRaD program). NRaD's Joint Littoral Awareness Network (JLAN) uses a combination of magnetic, acoustic, seismic, and chemical sensors to detect military activity on land and acoustic, electrical field, and magnetic sensors seaward of the high water mark. Sensor reporting is through a low probability of intercept (LPI) radio-frequency (RF) link (acoustic for the sea version) to area reconnaissance platforms (submarine, aircraft, UUV, or satellite). ONR's Deployable Sensor Project (DSP) uses passive acoustic, seismic, and magnetic sensors to detect surface and subsurface traffic patterns and the sound of mines or mine anchors impacting the bottom. Data are acoustically communicated to a monitor for satellite uplink. Utilizing JLAN for land mine surveillance and DSP in all shallow-water mining depths, including the deeper waters of straits and choke points, seems a reasonable utilization of both systems. Additionally, it should be pointed out that the broader capability of JLAN would provide useful continuing surveillance information for highly maneuverable Marine units ashore, and the DSP system could be used also for ASW surveillance.

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[7] The JSTARS radar is capable of distinguishing tracked vehicles from rolling stock, identifying helicopters and slow-moving aircraft, and pinpointing rotating antennas and jammer locations, as demonstrated in recent tests. It can also track surface ships and craft over the same wide area. While the JSTARS radar will begin to track ocean waves when the wave height exceeds sea state 3, the manufacturer has developed a filter to negate this effect and can install it on request.

The information gained through intelligence and surveillance will never be perfect, and ground truth in the form of reconnaissance in the period immediately preceding commitment of MCM forces will be required. Encouraging progress in covert, semicovert, and overt minefield reconnaissance systems has been made over the past few years. Particularly noteworthy reconnaissance systems are discussed below.

Mine Reconnaissance

Near-term Minefield Reconnaissance System

The Near-term Minefield Reconnaissance System (NMRS), under development by the submarine community, is a minefield reconnaissance UUV that can be launched and recovered through the submarine's torpedo tube. The torpedo body is fiber-optically controlled, with data recovery in real time. The system is equipped with ahead-looking and side-scan sonar for moored and bottom mine detection and with either TV or LIDAR for mine inspection. In addition to the submarine's mine surveillance role, NMRS gives it a covert reconnaissance capability as well.

Since the submarine is likely to be the first naval platform to reach an intended assault area, it will, of necessity, have to transit more distant areas, including straits, in which mines may have been planted in anticipation of a naval presence. NMRS will stand it in good stead in its own defense as well as proofing such areas for following submarines and surface ships. Further, the deep scattering layer, which rises near the surface at night, has been demonstrated to adversely affect both hull-mounted and variable-depth sonars using mine hunting frequencies. The submarine, with its depth capability, may be less affected by these scatterers than will those reconnaissance systems tied to the surface, such as the Remote Minehunting System (RMS).

Rather than develop in parallel a covert UUV mine reconnaissance system organic to itself, the MCM community should evaluate a low-cost NMRS for use by surface ships and craft. NMRS could be utilized with ease from the MCM-1, the MHC-51, an amphibious ship, or even the small SWATH craft discussed below.

Dolphin Reconnaissance Vehicle

Originally slated for the Advanced Concepts Technology Demonstration (ACTD) Phase I, the Dolphin semisubmersible (also known as the Remote Minehunting System [RMS]), equipped with an ahead-looking sonar and a towed side-scan sonar deployed from a keel mount, has already been tested as a semicovert minefield reconnaissance system and is now mounted on the USS *Cushing* (DDG-963). Since Dolphin uses a snorkel to support a diesel engine for propulsion, it has the advantage of being controlled by a radio link and using GPS for more precise navigation. Further, data from its sensors can be transmitted in real time. Because of the snorkel and diesel engine the system is not perfectly covert, it may have occasional trouble with surface debris, and care must be taken not to snag its towed sonar in shallow waters and in kelp beds.

Airborne Electro-optical Reconnaissance System

Although it is not covert and therefore could be vulnerable to hostile action, helicopter-borne electro-optical technology, such as that used in the Magic Lantern and Magic Lantern Adaptation R&D programs, has an important role to play in minefield reconnaissance, mine surveillance, and mine neutralization. It is unique in its capability for rapid, wide-area assessment from safe standoff (in unopposed waters). With further development it is expected that a two-dimensional search laser will detect proud mines and obstacles on the beach and in inland minefields and that a three-dimensional gated system will detect floating mines, moored antishipping mines, and bottom mines where optical and clutter conditions allow penetration. Whether these two capabilities should be merged into a single system is a decision to be made on the basis of technical feasibility and cost.

Clandestine Mine Reconnaissance and Countermeasures System

None of the three minefield reconnaissance systems discussed above are very effective at detecting buried mines; yet the shallower end of the littoral regime is where mines are most likely to become buried by natural forces (wave scour, traveling sand ridges, and mud bottoms). Also, in the future naval forces must be prepared to face deliberately designed self-burying mines, a relatively trivial adaptation. A field composed of buried mines would seriously degrade current mine hunting sonars and force an increased emphasis on slower and more laborious mine sweeping. A clandestine mine reconnaissance and countermeasures system (CMR/CS) is proposed by the panel as a possible reconnaissance solution to that problem.

CMR/CS is intended primarily for reconnaissance in depths between the surf zone and 40 feet of water, but it can cover waters of considerably greater depth. Envisioned is a small SWATH (for better seakeeping) platform with an overall length of about 36 feet, a beam of 15 feet, draft of 6.5 feet, and displacement of about 28 tons. The platform should have a range of about 100 nautical miles, with a payload of around 3 tons, and a maximum speed of 25 knots, with a cruising speed of 15 knots. The platform should be designed to be manned (three-person crew) or unmanned and remotely controlled. For the latter, the platform would be controlled by a fiber-optic link with an encrypted LPI RF link for backup. A more detailed description of this small MCM ship and its capabilities and uses is given below in this chapter. Mine detection, classification, and either marking or placement of delayed neutralization charges could be done by two Mk-7 mammal systems aboard each platform trained in the detection of moored, bottom, and buried mines. An expendable mine neutralization system could also be deployed from the CMR/CS. The effectiveness of bottom charges for neutralization of buried mines must be determined. Experience over the past 40 years supports the belief that mammals can be trained to operate effectively with an unmanned system, but the provision of a three-man (operator plus two trainer or handlers) crew has certain advantages.

CMR/CS could be transported by a combatant or amphibious ship (or by air if necessary) and launched from over the horizon for a high-speed (15 to 25 knots) run into the search area. Search speed for the system would be 3 knots, covering a search path 50 yards wide. With a 2-hour on-station time, each unit could cover around 600,000 square yards. The system would be capable of operating day or night, but night operations are envisioned for greater covertness. Further covertness could be achieved by utilizing stealth technology in the construction. The search speed noted above is based on detection and classification only. If the mammals are to place a transponder or a command-detonated neutralization charge on each mine contact, the speed of advance would be reduced.

The CMR/CS concept provides for reconnaissance against moored, bottom, and buried mines unmatched by any other search system. For that reason the panel believes that the Navy's support of biosensor research should be continued with the ultimate aim of replacing the mammals with a mechanical system of equal capability aboard the SWATH vehicle. Beginning with the research conducted by the Naval Undersea Center, slow but steady progress has been made in understanding the mammal's method of echo location. For instance, in the early 1970s, thin plates of different metals and different geometric shapes were used to compare the discrimination capability of porpoises and divers. The diver was provided with a helmet containing a sending and two receiving transducers. Test results indicated that the instrumented divers performed as well as, and in some cases better than, the porpoise. Subsequent research, including that with neural nets, indicates that developing a mechanical equivalent of the porpoise may be feasible. This technology requires further research before it can be considered for development.

Complementary Systems

The panel sees significant value in an airborne laser that is capable of rapidly conducting reconnaissance seaward of the surf zone against floating mines and moored mines (bottom mines if possible) and is accompanied by a neutralization system, an example of which might be the 20-mm system built around the rapid airborne mine clearance systems (RAMICS) concept using supercavitation projectiles. This capability is essential to clear floating mines ahead of the surface

MCM forces. The presence or absence of mines and obstacles in the SZ and CLZ can be detected adequately by satellites—even the Systeme Probatoire d'Observation de la Terre (SPOT) satellite, with 25-m resolution, detected the fortification of the Kuwaiti beaches by manned and unmanned aircraft—and by the coastal battlefield reconnaissance and analysis (COBRA) UAV with its multispectral video sensors and battlefield surveillance, forward-looking video if development of that system is completed. Similarly, the Army's Airborne Standoff Minefield Detection System (ASTAMID) UAV using IR sensors could also be employed for this purpose.

In perfecting a helicopter-borne electro-optical system for both reconnaissance and clearance seaward of the surf zone, a laser-stripe-type imaging system should be considered for possible advantages over synchronous line scanners and gated camera systems. The streak tube imaging LIDAR (STIL) is a three-dimensional imaging system that uses a pulsed laser transmitter and a streak tube charged-coupled device (CCD) receiver to time resolve the backscattered light from an ocean volume illuminated in azimuth by a fan beam of laser light formed using a fixed cylindrical lens. By orienting the fan beam perpendicular to the vehicle motion, the in-track dimension is sampled by matching the pulse repetition frequency of the laser to the forward speed of the vehicle, thus sweeping out a three-dimensional ocean volume in a push-broom fashion without the aid of a scanner. In this manner, a high-resolution three-dimensional image of the entire illuminated water volume and bottom (if shallow enough) is obtained. Since the return is recorded at all ranges, a laser-stripe-type system inherently has an extremely large depth of field, providing target detection or classification from the near field out to photon counting limits or the bottom.

The panel believes that these minefield reconnaissance systems—NMRS (submarine and organic), airborne LIDAR, RMS, and CMR/CS—will provide the Navy with the balanced, dedicated organic reconnaissance capability it needs. Combined with intelligence and surveillance, they will provide the ground truth required to achieve unprecedented efficiency in the operation of its MCM assets.

Task Force Organic MCM

Today's MCM mission execution relies largely on a dedicated MCM force, which includes the mine command and control ship, the USS *Inchon* (MCS-12), the Avenger (MCM-1) class mine hunting and mine sweeping ships, the Osprey (MHC-51) class coastal mine hunters, and the air MCM MH-53 helicopters. Significant efforts are being made to update the current force and make it more effective by forward-basing some MCM assets and introducing new technologies as they become available. Nonetheless, current MCM assets are not integral to naval combat forces. It takes significant time to move them—as much as 51 days to heavy-lift the MCM and MHC ships—to an area of operations. In order to provide the fleet with a robust organic capability to move to an objective quickly and safely, battle group combatants should be provided with the following organic capabilities:

- *Remote mine hunting*. Envisioned is a remotely controlled vehicle such as the RMS now being developed by the Navy for fleet deployment or, as technical advances permit, a semiautonomous underwater vehicle with acoustic and other sensors and systems for mine detection, classification, and neutralization, with the endurance and capability to search ahead of the ship from which it was deployed at moderate transit speeds of up to 15 knots.
- *MCM-capable helicopter*. This helicopter should be of modular payload design that could receive various sensor packages such as mine hunting LIDAR equipment, acoustic sensors and towed equipment, and mine sweep gear. Strong emphasis should be given to miniaturization and the development of physically lighter equipment to optimize the sensor payload mix.
- *Mine neutralization system*. Building on current mine neutralization work, provide an expendable vehicle that can be deployed from either the ship or a helicopter, can sense a previously detected mine, and can place the required neutralization package on or near the mine. In this connection, it has long been demonstrated that 0.50 caliber standard projectiles can sink floating mines, and occasionally detonate them, but have limited water penetration, which makes them less useful against moored mines. RAMICS, using a supercavitating projectile with a pyrophoric charge, promises to solve both of these problems. In using a helicopter-mounted LIDAR for detection and aiming, the problem is to establish an accurate fire control solution at a range that permits the helicopter to stand outside the shrapnel envelope. Studies and tests thus far have been favorable.

Programs related to providing these capabilities include the following.

Airborne Laser Systems

The Navy's Magic Lantern Adaptation system, the Army's ASTAMID, and the Marine Corps' COBRA are all in the concept and development stages and are designed to detect mines in the surf zone, in the craft landing zone, and on land. For detecting mines seaward of the surface there are three competing laser-based technologies: the range-gated camera, the spot-scan, and a laser-stripe-type system.

The Magic Lantern system is based on a range-gated CCD camera. It provides better resolution in the horizontal plane than in the vertical direction (depth). It is primarily a shadow detector and can be used against floating or moored mines. The Magic Lantern Adaptation system mentioned above is based on Magic Lantern technology and addresses the minefield detection problem in the surf and craft landing zones. There are currently three Magic Lantern systems on reserve SH-2 helicopters, and a system was deployed during Desert Storm. Integration into the active fleet would require that the sensor be modified to fit on the SH-60 helicopter.

Spot-scan technology, based on the photomultiplier tube, was originally designed for ASW but is being modified for the MCM mission. It uses a scanning spot beam to construct an image of the scanned area. The spot-scan approach provides fine resolution in the vertical direction but coarse resolution in the horizontal plane. The laser's pulse repetition frequency is a limiting factor on system resolution.

In addition to these approaches, a third, based on laser-stripe technology, is in an earlier phase of development. The laser-stripe approach, as embodied in STIL, uses a fan beam projection perpendicular to the direction of motion and a CCD array to provide fine resolution in the vertical and cross-track directions. The along-track image is formed by successive pulses as the searcher moves ahead. STIL holds the promise of fine resolution that may be able to detect bottom mines as well as those in the water column.

All of these systems take advantage of a notch in the attenuation curve in the blue-green optical region of the electromagnetic spectrum. Even so, attenuation is severe, and LIDAR systems will likely always be limited in depth. However, the depth ranges reachable are important for MCM, and in addition, such systems may be used to complement look-down sonar searches at lower depths.

Expendable Neutralization Vehicle

The mine neutralization vehicle now available to MCM-1 and MHC-51 MCM ships is the AN/SLQ-48 mine neutralization system, a deck-mounted vehicle launched and recovered by a winch and crane system

The mine neutralization vehicle is subject to several limitations against the shallow mines that are now the focus of attention. Its forward progress and maneuverability are adversely affected by longshore and tidal currents. Because of its magnetic signature, it cannot approach a mine close enough for precise charge placement, and the cycle time from launch to recovery is excessive for the kind of clearance speeds required in modern scenarios. The launch-to-recovery cycle time after the mine has been detected and classified, and then the time required for the ship to back off to a safe range, combined with operations in daylight hours only, mean that an MCM-1 can clear only about 12 mines per day. Further, there is no assurance that the mine has been neutralized, and, even if it has, a mine that looks like a mine on a mine hunting sonar is left to possibly create later confusion, along with an explosive charge weighing up to a thousand pounds that could later detonate by impact.

Despite these limitations the SLQ-48 has unique capabilities and should be retained for neutralization of mines in deeper water such as straits, the outer continental shelf, and shallower parts of the continental rise. The French PAP-

104 would be better suited to shallow-water mine neutralization, but here, too, is a vehicle that must be launched over the side and recovered. What is needed is an expendable mine neutralization vehicle with a signature low enough to actually touch the mine without activating it, and with adequate terminal homing sensors to place a small cavity charge against the mine's main charge.

The old wire-guided Sea Nettle concept of the 1960s was an excellent early attempt to achieve the capability noted above. However, if the anecdotal record is correct, the program committed the fatal error of continuously adding capability until the system was priced out of competition.

Today, however, there is another chance to produce an effective and inexpensive expendable mine neutralization system. Fiber-optic cables have replaced the wire for guidance, LIDAR has been introduced and added to sonar for terminal homing and placement of a small neutralization charge against the explosive compartment of a mine, improvements have been made in small sonars, and miniaturization of electronics and sensor systems has increased significantly. The Navy should pursue the development of a small, low-cost, expendable mine neutralization vehicle for use by advanced mine countermeasures (AMCM) helicopters, small MCM surface craft, the MCM-1 and MHC-51, and in the future, all MCM-capable ships and air platforms.

Airborne Mine Neutralization System

The Airborne Mine Neutralization System (AMNSYS), currently in development, is intended to provide MCM helicopters with a mine neutralization capability. However, the airborne mine neutralization approach has limitations. The neutralization vehicle is lowered into the water and fiber-optically guided to a GPS coordinate provided by another helicopter towing a mine hunting sonar. Guidance by the launch vehicle to GPS coordinates is provided by a dipping tracker sonar. The neutralization vehicle, after reaching the near vicinity of the coordinates, must then detect the mine and home on it with its own sensors—whether sonar, TV, or LIDAR. Problems of target reacquisition are likely to arise because the GPS coordinates provided by the mine hunting helicopter are based on detection from a side-scan sonar towed at some distance from the helicopter. It would be better if the tracker sonar were upgraded such that the neutralizing helicopter, using GPS coordinates, could reacquire the contact before launch of the neutralization vehicle.

As an adjunct, consideration should be given to providing airborne systems with a variable-depth mine hunting sonar so that a single helicopter can do mine detection, classification, and neutralization as do MCM ships. Cost trade-offs, not technology, will be the determinant. The technology required for the neutralization vehicle is in place. The concern is keeping the costs down, ensuring that the cycle time (launch to detonation) does not exceed 10 minutes, and insisting on a sympathetic detonation of the mines.

The Navy should take a fresh look at the design of an expendable mine neutralization system capable of being used, with minimal adjustment, by AMCM helicopters, by the MCM-1 and MHC-51 MCM ships, by designated MCM-capable combatants, and by small MCM surface craft yet to be introduced.

Synthetic Aperture, Low-frequency, and Self-registering Sonars

These sonars can significantly improve the location and classification of mines in the shortest possible time and from a safe distance. In the panel's opinion, such sonars will be the central element in all future aspects of mine hunting, including reconnaissance, minefield mapping, mine avoidance, and mine neutralization.

Current long-range search sonars operate in the frequency range of 10 to 100 kHz with detection ranges of up to 2 km, but they have poor resolution and are therefore prone to high false-alarm rates. Higher resolution requires impractically large apertures. Medium- and short-range classification sonars typically operate at 100 to 1,000 kHz. They have better discrimination and therefore can eliminate a large proportion of the nonmine contacts, but their range is limited and their area coverage rate is low. It is possible to combine the long-range attributes of the lower-frequency sonar with the high resolution afforded by high-frequency sonars through the use of synthetic aperture techniques. Until now, the technological stumbling block has been the need for precise navigation control or enormous computing power to make self-registering methods practical. Today's technology provides the latter. DARPA has a program under way that is intended to demonstrate this capability. If successful, this technology is expected to become a key element in the realization of a truly organic fleet MCM capability. It is recommended that the MCM community monitor this program and adapt successful aspects of the technology to current and future MCM platforms.

Current side-looking sonars are unable to look ahead and could miss a target that presents a weak signal if the sonar was deployed in such a way as to look only once at each location and aspect. Synthetic aperture processing could mitigate this potential shortcoming because it necessarily involves multiple passes over the same location at various aspects.

Brute Force—Breaching and Clearing the Surf and Craft Landing Zones

Brute force methods are generally those techniques that attempt to remove or clear mines en masse, using a nondiscriminating force that can physically overcome or remove them as an effective threat. Brute force methods are needed when the threat is so dense and time lines are short, where friendly forces are denied access to a mined area that needs clearing, or where the harshness of the environment prevents other MCM operations. Brute force methods, because they do not depend on specific characteristics of the mine such as its signature or fusing method, are also a hedge against undetectable, difficult-to-spoof, stealth mines; unknown future mine technology developments; or even simple mines with very high ship counts and interlook dead periods. Although they are sometimes not highly technical, brute force breaching methods may require complex engineering, precise timing and fusing of explosives, development of unique chemical systems, applications of GPS and other locating and mapping methodologies, and high reliability.

The technologies, concepts, and systems discussed here must be developed to provide the path from the surf zone (10 to 15 feet) to the craft landing zone and up the beach, where there is a proliferation of mines and a dramatic increase in their density. In addition, minefields in these regions are usually mixed with several types of obstacles. Methods for breaching the surf and craft landing zones too often ignore the obstacle problem.

The panel has singled out two brute force technologies and techniques that appear to hold the most promise: (1) explosive channel excavation and (2) the use of causeways made of rigid polyurethane foams. The former relies on accurately placed bombs with timed explosives to clear mines and obstacles; the latter provides a means of bridging the minefield rather than clearing it. Other relatively simple mechanical and explosive approaches that should be considered for application in certain situations are also described. The two major technologies that are of the highest priority are discussed below.

Explosive Channel Excavation

The 1992 Naval Studies Board *Mine Countermeasures*[8] study suggested that a buried line charge analog could be formed by airdrop or ballistic delivery of spaced bombs, penetrating to about the depth for maximum cratering radius, and detonated nearly simultaneously to form a cleared channel by excavations of mines and obstacles in the SZ and CLZ, and on up the beach. Although listed here as a brute force technology, it involves precise spatial and temporal placement of the explosive charge and high reliability of detonation. The requirements for precision are not so high in the vertical dimension because of the wide maximum in crater radius as a function of depth of explosion. Specifically, it was estimated that penetrating bombs with 10,000-pound TNT-equivalent explosives,[9] spaced about 60 feet apart, buried to about 20 feet below the sea floor, and

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[8] Naval Studies Board. 1992-1993. *Mine Countermeasures Technology*, Vol. I-IV, National Academy Press, Washington, D.C.

[9] During World War II, about 500 bombs of this size were used by the Royal Air Force's 617 squadron with much success, including the final capsizing of the *Tirpitz*. B52s, according to Boeing, could carry one under each wing. Cargo aircraft could also release a drogue-pulled string. The Soviet "Granit" self-alignment scheme for bomb patterns might also be used. On the ballistic side, missile tests in the 1980s demonstrated delivery of a 15,000-pound warhead at 300 miles.

detonated to within 0.01 second of each other could excavate a 50-yard wide channel in which the bottom would be lowered 10 to 15 feet. The channel could be extended up the beach and would fill with water so that assault craft could ride to the end beyond the defended zone. Subsequent work by the Naval Surface Warfare Center including a test at the UK Shallow Water Test Range using four spaced, buried bombs has confirmed the scaled dimensions, the effective removal of mines and obstacles, the formation of sizable berms on the channel sides, and the absence of a large lip at the channel end.[10]

LLNL has proposed independently that patterns of available bombs could be used to excavate cleared channels.[11] Thus a double lane of 2,000-pound bombs, buried about 5 feet deep and spaced about 30 feet apart, if a 30-foot circular error probability is assumed, could form a 100-foot (lip to lip) channel 10 to 15 feet in depth from which most mines and obstacles have been removed. The Panel on Weapons discusses this concept in *Volume 5: Weapons* of this nine-volume series, adding the feature of proofing the channel by heavy line charge detonation after emplacement by robotic advanced amphibious assault vehicles (AAAVs).

Experiments at the Coastal Systems Station in Panama City, Florida, have demonstrated that mines and obstacles can be pushed away to form a clear channel by sequential positioning of bottom explosives to systematically provide momenta away from. The previously cleared area, in sufficient depths of water in the time between sequenced explosions, is affected by water motion in the surf zone. An analogous concept could probably be applied to sequential excavation in shallower water and up the beach.

In very shallow water, which is defined as the depth zone from 40 feet to between 10 and 15 feet deep, the threat is not expected to involve obstacles or very hard mines, and the mine density is expected to be lower than in the SZ and CLZ closer to shore. Mines in the very shallow region could still be buried, however, and there is always the possibility that increasingly stealthy mines will become available to potential adversaries. Explosive excavation could be effective in this zone, but the amount of ordnance required would be large because the very shallow water zone is typically far more extensive than the surf and craft landing zones.

The concepts described above, some in ongoing programs (e.g., line charges discussed below) as well as pulsed power, can be included under the generic concept of space- and time-controlled explosive patterns. If significant increases in the yield per unit mass of explosives become available, the practicality of all of these techniques will be enhanced. Further, modeling and simulation will be

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[10] Furr, W., R. McKeown, and L. Taylor. 1996. “Mine and Explosive Breaching by Explosive Excavation,” presented at the Technology and the Mine Problem Symposium, Naval Postgraduate School, Monterey, Calif., November 18-21.

[11] Clarke, Douglas B., and John W. White. 1997. “A White Paper on Surf Channeling,” Lawrence Livermore National Laboratory, Livermore, Calif., February 14.

applicable to design of the explosive characteristics space-time pattern to obtain the best results and to facilitate operational planning for their use. Some of the data required to better understand explosive excavation phenomenology could possibly be obtained through experiments and modeling using a high-*g* centrifuge.[12]

Foams

The panel was impressed with DOD-funded work done at Sandia National Laboratories on petrochemical-based binary compounds that has led to the development of quick-setting rigid polyurethane foam. The chemicals, transportable as liquids, when mixed and exposed to air form a relatively tough, quick-setting, and rigid structure that floats on water. The volume expansion between the component liquids and the final rigid foam is a factor of 20 to 60, and the resulting structure has a bearing strength sufficient to withstand the repeated passage of vehicles, including tanks (in tests, passage of more than 50 tanks with a rut depth that did not exceed 12 inches). These foams have been demonstrated to withstand projectile impact and detonation with attenuated damage patterns, and tests indicate that they are not structurally weakened by bullets. Foams now in use will burn, but the resulting fire has been shown to be self-extinguishing. Tests also indicate that the foam can absorb some explosive blast energy. The foam will also incapacitate the sensors on pressure and tilt-wand mines, if the mine is engulfed in and immobilized by the foam; will provide a standoff for magnetic mines; and will reduce the profile presented by obstacles to assault traffic.

Although still in the developmental stages, this technology may have significant operations benefits. Many brute force techniques require significant maritime lift capacity, which offsets the space available to carry amphibious vehicles and other warfighting equipment. The foam system, if successful, has the advantage of being transported in an easily handled liquid form with minimal space requirements. Preliminary tests indicate that a foam road can be built in shallow water out to the surf zone.

Following are some other brute force methods involving explosives.

Explosive Nets and Rocket-propelled Line Charges

Now in the R&D program, these are methods for neutralizing mines in the surf and craft landing zones, with application to land minefields as well. The rocket-propelled line charge, known as SABRE, is a line thrown ahead from a

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[12] See, e.g., Holsapple, Keith A. 1994. “Catastrophic Disruptions and Cratering of Solar System Bodies: A Review and New Results,” *Planetary and Space Science*, 42, no. 12, pp. 1067-1078.

landing craft, air cushioned (LCAC), by a rocket motor; the explosive net, known as DET, is a net with neutralizing charges at mesh corners (the net itself may be made of primacord) capable of being rocket propelled into place in the same manner. Both are adaptable to use against land mines. There is a net version that can be deployed by air, known as Thunder Road.

Both systems are sound, but given the demanding conditions of the initial phase of an amphibious assault, both have disadvantages. The delivering platform must be brought close to the mined area prior to launch; the logistic load is burdensome where multiple shots are required; the lateral neutralization distance is limited by the upward focusing of ground level explosives; and both will drape over obstacles, possibly leaving mines beneath the drape undamaged if the depth of draping is too shallow or out of the water.

SABRE and DET should be developed for breaching both land minefields and the surf and craft landing zones where obstacles are not present. Particularly against land minefields, the Thunder Road and glide net concepts for aircraft delivery have merit and should compete for selection. The objective of a 1,000-foot launch standoff for both SABRE and DET appears reasonable and attainable.

ATACM Block 1

Missiles, such as the Army Tactical Missile (ATACM) Block 1 with a range of 75 miles and carrying 950 bomblets, represent an interesting variant on the DET concept for clearing both land mines and sea mines in the SZ and CLZ. Pattern control is an obvious problem, as are comparative costs. Further, current designs incorporate antipersonnel bomblets that would have to be redesigned for use against mines. Given its standoff range and speed of delivery, however, it is a concept worthy of further analysis. The ability to fire ATACMs from a Navy ship has been demonstrated.

Mechanical Methods

In the past, a number of mechanical devices have been used with varying degrees of success against both land and sea mines, and several modern versions of some of these devices are under development today. Such devices have consisted of vehicle-mounted flails, rollers, and plows against land mines and obstacles, and trawls against shallow sea mines. A detailed description of mechanical methods is given in Appendix E.

THE FAR TERM: TECHNOLOGY AND CONCEPTS

Next-generation MCM Platforms

There is a need to develop a replacement system for the current classes of mine hunting and mine sweeping ships and helicopters to accommodate the Navy's future roles and responsibilities and to take advantage of new MCM technologies. Helicopters with improved, lighter, MCM sonars, LIDARs, active magnetic or mechanical and acoustic sweeps, and possibly supercavitating projectile mine killers will be an important element of future MCM capability. The future MCM helicopter will have a modular payload capability so that it can be rapidly configured to meet special demands. Surface platforms will be small, stable, long-endurance, unmanned platforms, possibly based on SWATH technology, possibly stealthy, towing sonars under remote control. Underwater platforms will include swim-ahead UUVs with mine detection, classification, and neutralization capability. The panel anticipates the development of a specially configured MCM support (*Catskill*-like) ship, with battle force speed, MCM command and control capacity, and the capability to transport and maintain small MCM ships and helicopters having characteristics such as those outlined in Table 2.1.

The concept of operational employment for the new MCM support ship and embarked MCM assets is to deploy them with either a battle group or an amphibious ready group, depending on time requirements. This will provide an MCM capability in transit, in-area surveillance, hunting, sweeping, and neutralization. If positioned remotely from an emerging need for MCM operations, the support ship with its embarked assets will be able to transit immediately and at battle group speed. In the event the MCM support ship is not available prior to the battle group's need to move, the recommended organic MCM capabilities will allow safe and rapid transit.

Modern Catskill Concept

The panel considered specific support ship and small MCM ship designs applied to a modern-day version of the Catskill concept. Over its long history the MCM force has repeatedly demonstrated that the countermeasure functions of mine sweeping, mine hunting, and mine neutralization can be carried out by air and surface platforms much smaller than the 1,300-ton MCM-1 carrying a crew of 83. The Inshore Minesweeper (MSI), mine countermeasures ship (MCS), and Minesweeping Launch (MSL) of the 1960s, which ranged in length from 36 to 110 feet, clearly demonstrated the fact, and AMCM helicopters are a more recent example. Craft of opportunity have been an enduring example, as well. In designing a future MCM force organic to the fleet, the Navy should capitalize on the proven capability of smaller platforms and take full advantage of all reductions in the weight, volume, and drag of MCM systems allowed by modern technology.

The use of the minimum-size surface craft required to carry out the MCM function has two disadvantages that must be mitigated: they have limited seakeeping capability, and they must be transported to the site of conflict. In the early 1960s an important attempt was made to deal with these problems. Two 9,000-ton logistic support vehicles, the USS *Ozark* and the USS *Catskill*, were converted to MCS ships. In addition to a landing pad and a hangar for two AMCM helicopters, the MCSs were equipped to carry 20 MSL MCM craft. The MSL was a 36-foot open launch (Boston Whaler type) equipped for mine sweeping using light AMCM sweep gear, mine hunting using a strap-on AN/SQQ-16 variable depth sonar, and mine neutralization by vectoring a charge lowered from a small boat. However, the concept had one serious and one fatal flaw. The MSL turned out to be a very wet boat, which limited its operations to sea state 2 and below, and the MCS was top heavy due to the 22 MCM platforms carried at or above the main deck. Unfortunately, these shortcomings resulted in the abandonment of what could have been powerful and cost-effective MCM platforms.

The shortcomings in the earlier implementation can easily be overcome with current technology. Utilizing a SWATH hull form, an MCM craft of the general size of an MSL (i.e., 36 feet in length) can perform the full range of MCM functions, operate in sea states 3 to 4, and survive in higher seas.

The more important mission of the small MCM platform is expected to be mine hunting, although it would have a mine sweeping capability utilizing either lighter AMCM sweep gear, or influence gear such as that being considered in the Advanced Lightweight Influence Sweep System (ALISS) research program. The sonar would be a variable-depth type about the size of the modified SQQ-14 or smaller. An expendable mine neutralization capability would be provided. Platforms of varying sizes could be built or reconfigured to fulfill the requirements of transporting, supporting, and acting as the command and control element in MCM operations. The support ship might be capable of carrying 2 to 10 of the small MCM vehicles and also possess helicopter deck space and support areas. The precise configuration and size of the support ship will depend on a detailed analysis of the concept of operations for these platforms.

Pulsed Power

The use of intense acoustic or shock waves to disable mines at safe standoff and also destroy obstacles and barriers represents an attractive concept for MCM. Pulsed power is an application of space-time distributed explosive energy, produced by electrical discharges, chemical reactions (small explosions), or other methods, to produce focused acoustic or shock energy. The idea is similar to, but on a much larger scale than, the successful application of focused acoustic shock waves to kidney and gallstone therapy—known as lithotripsy—wherein the calcareous stone is destroyed by repetitively subjecting it to a shock waves, which eventually break it into pieces small enough (in the case of a kidney stone) to be passed painlessly via normal urination.

The range at which sufficient energy for mine neutralization can be brought to bear will be an important consideration for the protection of platforms from which any pulsed power device is deployed. A number of approaches using a variety of source technologies have been proposed. These include, most recently, chemical explosive arrays to form shock pulses and spark discharge pulses from either a single source or a phased array of sources. Two concepts of operation have been considered. In one, low-power pulses are transmitted, and the returns are received by an acoustic receiver array and analyzed to indicate the location of a target in a manner identical to a conventional sonar. A pulsed discharge array, at higher power, can then be focused on the target.[13] A second, more recent concept involving explosives simply generates high-power pulses in a beam that advances with the motion of the source vehicle, clearing mines and obstacles in the way.

At the time of this writing, DARPA is conducting a program to address the critical issues and assess the practicality of the method. These issues include determining if nonlinear wave superposition works in the same sense as linear superposition, thus resulting in the assumed 10 log *N* array gain and, if so, determining whether in practice shock sources can be timed or appropriately phased. If focusing is used, the sharpness of the focal point itself is important and would have to be modeled with nonlinear acoustic models. The effect of in situ bubbles, especially dense in near-shore areas, is unknown (a 1 percent void fraction can double acoustic attenuation). The effects of cavitation bubbles produced by the shock wave itself on subsequent shocks that must pass through the cavitated water are also unknown. Multipath propagation and surface and bottom reflection and scattering will also affect focusing on the effective beam geometry. The destructive mechanism for mines is not certain, nor are the required pressure and impulse. Repetitive pulses may be required to destroy some kinds of mines.

There are implementation considerations as well. There are limitations in pulsed power to avoid damage to the carrying vehicle and source array, as well as limitations due to water depth and required standoff distances; there are also limits in pulse shaping and repetition frequency because of source characteristics and between-shot recovery times.

Although the list of issues that have to be addressed to assess the future application of this method is seemingly long, and there are concerns regarding the physics of nonlinear wave superposition in water and the effects of limited depth and irregularities in the propagation medium, initial results from the DARPA

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[13] Although it was not presented to the panel, the Navy has apparently evaluated the electric spark approach as requiring heavy equipment to achieve mine detonation at acceptable ranges.

program are encouraging. At this point a systematic measurement program to acquire necessary data is required. If this technology can be developed for effective use by MCM forces, it could significantly multiply current capabilities. As mentioned above, feasibility studies are currently under way and, if the technology proves feasible for operational use, further development should be pursued.

Autonomous and Semiautonomous Networked Undersea Systems

The most pressing need is to extend the reach of MCM sensors without putting humans in harm's way. While requiring advances and development beyond those currently possible, technological progress in sensors, signal processing, and computational power will make autonomous and semiautonomous systems possible. Networked undersea surveillance systems using small, autonomous and/or semiautonomous undersea vehicles could significantly enhance covert mine surveillance, detection, and neutralization capability.

Such vehicles would posses a hierarchical intelligence, and varied capability; they would be able to communicate with each other and with command-and-control nodes via Internet-like circuits. They would operate autonomously, reporting only when interrogated or programmed to do so. Autonomous vehicle systems could be combined with other distributed sensor systems, perhaps predeployed in an area of interest.

Vehicle technology pursued in past UUV programs[14] provides a basis for future efforts. New energy sources, propulsion methods, automatic target detection algorithms, and methods of underwater navigation and autonomous control will make the UUV an ever more practical adjunct to MCM operations. Within the time horizon of this study, it is expected that undersea communications technology, acoustic or otherwise, with adequate data transfer rates, will be available.

Multiple vehicle approaches that exploit the efficiency of systems operating in parallel might involve stealthy vehicles or small, bottom crawling robots that detect mines, attach themselves to them, and then at a later time, perhaps on command, neutralize them. Such small autonomous or remotely controlled devices might be effective against very shallow water (VSW) mine fields, perhaps using the electrical resistivity method (discussed below) to sense buried metallic and nonmetallic mines. Neutralization of buried mines requires investigation. In-water use in the SZ may be limited because it is relatively easy to construct simple and inexpensive barriers between their launch point and the minefield. Nevertheless, it is clear that robotics has a strong future role to play in MCM, and research in this general area should continue. The viability of alternate ap-

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[14] National Research Council. 1996. *Undersea Vehicles and National Needs*, National Academy Press, Washington, D.C.

proaches will depend on specific requirements, concepts of integrated operations, possible counter-countermeasures, and the existing state of critical vehicle technology development.

Mammal Adjunct to the Small Unmanned MCM Ship

None of the minefield reconnaissance systems discussed thus far are capable of detecting buried mines, yet mines buried by natural means are likely to be encountered in those littoral regions where shoals are forming. Currently, only the Mk-7 mammal system is capable of detecting and placing charges to neutralize buried mines. Combining the Mk-7 with a small, enhanced-capability MCM vessel could provide a system that can be launched from over the horizon, that operates in sea states 3 to 4, and that is able to detect, classify, and place timed neutralization charges against moored, bottom, and buried mines into the surf zone. The effectiveness of neutralization of buried mines by charges on the bottom requires investigation.

If some of the advanced reconnaissance systems described in this report become available, the preferred use of the small MCM vessel Mk-7 system would be to proof channels already selected on the basis of earlier reconnaissance against buried mines and to place neutralization charges on or above all mines in the channel. Its use in this fashion moves the operation closer to the assault launch hour, by which time control of air, sea, and near-shore defenses has presumably been established.

Swimmer Electrical Resistivity Detection System

Minefield reconnaissance by swimmers (sea, air, land [SEAL] teams), particularly in depths between 60 feet and the surf zone, is effective but limited in search rate and incapable of detecting buried mines. To augment this capability the panel recommends that the electrical resistivity method suggested by the JASON[15] committee during the time of Desert Shield be evaluated. Electrical resistivity has long been used by the mining industry to detect buried ore bodies and other subsurface anomalies. The JASONs suggested that it be evaluated for use in the detection of moored (by their anchor), proud, and buried mines, both metallic and nonmetallic.

The JASONs hypothesized an array of electrodes about 6 feet long.[16] The

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[15] The JASONs are a self-nominating academic society that conducts technical studies for the Department of Defense (meets in July, August, September, and October and produces a report in November).

[16] The vertical (downward) dimension of the electrical field is several times greater than the spacing between the two current-carrying electrodes. Since the targets to be detected (mine anchors, proud mines, and buried mines) would be either resting on the bottom or buried by no more than a few inches, the distance between electrodes would not have to be more than 6 feet.

two outer electrodes (one at each end) would carry current, thereby establishing an electric field, which would be monitored by the inner non-current-carrying electrodes. The upper surface of the array would be insulated to prevent interference by surface waves. Metallic mines will register as an increase in conductivity, and nonmetallic mines will register as a nonconducting anomaly within the field. Detected anomalies would be correlated and analyzed by a small computer. Although false contacts may be a problem in some areas since the method is unlikely to allow positive classification, in the absence of any alternative for swimmer detection of buried mines together with the capability to detect both metallic and nonmetallic mines, the electrical resistivity method may provide a useful capability. The electrode array could also be mounted on a UUV.

Biosensors: Mammal Sonars

There are many ways of reducing the signature of a mine to make it less detectable, such as using materials and shapes that blend in with the environment, constructing it of nonmagnetic materials, or designing it to have a low acoustic cross section. Existing mine hunting sonars have a very difficult task detecting reduced-signature mines, and in the short term, the Navy may be forced to rely on sweeping and brute force methods when such mines are known to be deployed. However, in the long term, future detection systems are expected to counter this problem. The reason for optimism lies in the performance of biological sonars, such as those of dolphins. These mammals are able to detect prey by sonar, even small fish that have much lower signatures than any mine and can conceal themselves by burrowing in the sediment. In many ways, they outperform hardware. They are the most (perhaps only) effective system available for finding buried mines. They are effective in locating, identifying, tagging, and charge placement. Unfortunately, however, their range (<20 km) and endurance system are limited, they are sensitive to temperature, they have stringent on-site handling requirements, and they pose difficult logistical demands. It may be possible for potential adversaries to engineer mine signatures in such a way as to make detection by marine mammals more difficult, but given the limited use of mammal-based mine hunting systems, it appears unlikely that any nation will go to this expense in the near term.

All of these shortcomings could be overcome if the features of mammal sonars were incorporated into hardware. Since 1959 there have been a number of small research programs with this objective, but little has found its way into practice. For example, mammal sonars are known to adapt, presumably in some optimal sense, to the environment in which they operate. They change pulse types, durations, and frequencies. They use two ears, and they approach targets and view them from several aspects. These notions have had only elemental incorporation into sonar system design.

It is not unreasonable to postulate a man-made sonar with the same capabilities as a mammal sonar, especially with the growing understanding of cognitive processes and the development of systems such as neural networks that mimic them. The payoff in vastly improved sensor performance is so great that research aimed at revealing the mechanisms of biosonars with an aim toward emulating them should be given high priority.

Active Electromagnetic Mine Detection

Pulsed electromagnetic induction is a methodology that has been employed successfully in geophysical prospecting for conductive ore bodies. It is an active electromagnetic technique whereby a primary magnetic field is used to induce currents in nearby conductors. The currents decay because of resistive losses, creating secondary magnetic fields that are detected above Earth's surface. The rate of decay of the secondary field contains information about the size, conductivity, and magnetic permeability of the object. Although the application of this approach to mine and submarine detection was investigated by the Naval Ordnance Laboratory in the 1950s, recently a new processing technique using holographic imaging has shown considerable promise. It is recommended that progress with this technology be closely monitored and applied to MCM systems as appropriate.

OFFENSIVE MINING

The Case for Offensive Mining

At present, a segment of the naval community questions whether, in the high-technology weapon environment we are now entering, the Navy will have a need for mines in the future. Yet there has not been a time since the 1930s during which the Navy has been more in need of mines to leverage a reduced fleet with expanded global responsibilities. First there is the deterrent value of a credible mine stockpile and the ability to deliver it—covertly, if necessary. The deterrent value of that stockpile will be measured by the sophistication of its content and the adversary's uncertainty of being able to counter the mine types it contains. There is also the need to be able to supply our allies with effective mines to provide for their own defense or to slow down an assault until U.S. forces can arrive. Taiwan and South Korea come to mind, although both have the technical ability to design superior mines on their own.

Perhaps the Navy's greatest need for mines in the present environment is for effective blockade of strategic ports and straits without the need for exposing lives and high-value targets to defensive action. With reductions in force levels there is justifiable concern on the part of both the Navy and the Marine Corps regarding the ability to handle two simultaneous medium-level conflicts. In those scenarios in which the aggressor's ambitions are based in significant part on the use of naval forces, mines could be useful in stopping or seriously delaying such aggressive action until additional force can be brought to bear.

The growing dependence on submarines around the world and the slow but steady increase in the proficiency of their crews signal a serious problem for the Navy and Marine Corps team in any future attempt to project power against the land. Advanced mine designs capable of protecting the flanks of an amphibious assault force from submarines will significantly leverage the available combatants. Such mines could be equipped for preset explosive self-destruction when their job is done.

Near-term Needs and Recommendations

Sustaining a Mine Design Team

One of the many casualties of the post-Cold War downsizing has been the mine design capability so long resident at the old Naval Ordnance Laboratory at White Oak, Maryland. The White Oak team, in which resided the expertise and corporate memory accumulated since World War II, has been reduced to token representation of mine design specialists and supporting documentation at the Coastal Systems Station in Panama City, Florida.

The Navy and Marine Corps will need a small mine design team composed of the most highly qualified scientists and engineers it can attract to the job in order to (1) assist the technical intelligence community in interpreting new, and often fragmented intelligence data; (2) analyze and help develop countermeasures to foreign mines; (3) prevent technological surprise; (4) conduct research from which the Navy can select its future mines; and (5) serve as a Red Team for the MCM research and development community. The panel strongly recommends that such a team be built around the token element now resident at the Coastal Systems Station.

Remote Command and Control

With the placement accuracy made available by GPS navigation, it is now possible to lay offensive minefields in order to prevent defensive mining and yet leave unmined channels for use by our own forces. This technique has long been suggested but, due to navigational uncertainties, considered too dangerous to our own forces to be implemented. The alternative, of course, would be to develop a remote command and control of mines feature of such reliability that our own forces would pass over a command-off minefield with confidence. Commanders, particularly those of high-value ships, have been reluctant to accept this technology over the past 25 years. However, there appears to have been no hesitation in passing over the controlled minefields used to protect Allied harbors in World Wars I and II or the one used by Norway throughout much of the Cold War. The difference between the old and trusted system and the yet-to-be-trusted new system, besides vastly improved electronics in the latter case, is that the old system had a man in the command-on-command-off loop.

Littoral Sea Mine

To fill and improve on the void to be left by the Mk 56, the Navy should seriously pursue a littoral sea mine (LSM). A mission needs statement currently exists for such a mine, and an advanced technology demonstration (ATD) has been proposed by the Navy and industry. The prototype LSM will consist of a three primary subsystems: (1) a target detection system that leverages ongoing sensor technology demonstration efforts; (2) a mobile homing warhead that uses the lightweight hybrid torpedo currently being developed; and (3) a subsystem that leverages ONR's deployable autonomous distributed system technologies.

The target detection system will provide the capability to detect, localize, and track targets in the littoral environment to within the lethal zone of the lightweight hybrid torpedo. It will consist of a multi-influence passive detection subsystem and an active target verification subsystem. The passive detection subsystem will acquire and process target signature data and initiate the transition to the active acoustic verification mode. The active sonar will transmit low probability of target alertment pulses to make multiple range and bearing determinations until a target track converges with sufficient quality to verify that the target is within the mine's lethal zone. The target detection system will then activate the mobile homing warhead, pass targeting information to the vehicle, and prepare it for launch.

The primary function of the mobile homing warhead is to deliver a bulk charge warhead from the mine's deployed position to within the mission abort damage range of the target and to detonate the warhead at the appropriate time. Using the lightweight hybrid torpedo as the mobile homing warhead payload utilizes the speed, maneuverability, and zone-homing performance of the torpedo. This will increase the mine's lethal-zone-coverage capability over that of the Mk-56 mine. Also, since the lightweight hybrid torpedo can be vectored in azimuth from a vertical launch, which was not possible with the encapsulated torpedo (CAPTOR) mine using the Mk 46 Mod 4/6 torpedo, a single mobile homing torpedo can cover many target volumes. A RECO subsystem will provide the capability to control an LSM field from a surface or submarine platform.

The Marines and the Modern Homing Mine (HOMINE)

The Marine Corps depends largely on the Army for its land mines and the countermeasures to such mines, and for that reason, as noted in the Preface, this report deals mainly with sea mines and mines in the surf and craft landing zones. It appears, however, that evolving Marine Corps strategy and tactics for land combat (i.e., many light, small units, widely spread, very lethal, and highly maneuverable) will generate requirements for both land mine and land mine countermeasures that differ from those of the Army.

In the late 1960s and early 1970s, the Army developed to the prototype stage a distributed sensor antitank minefield called HOMINE. The sensors were small, inexpensive, easily scatterable devices consisting of either a pressure or a magnetic sensor and a simple radio transmitter. The radio signal was coded, and all sensors for a given kill system had the same code. When approached (or run over in the case of the pressure sensor) by a tank or armored vehicle the radio transmitter emitted a single, coded burst. The radio burst gave no indication as to which sensor had activated or where within the field the target was, but this was not needed. The multiple-shot kill system was concealed centrally within the sensor field, or centered along its periphery, and consisted of a short grain solid rocket motor, an IR sensor, a warhead, and limited control surfaces. On receiving a signal from one of the sensors the rocket boosted the kill system such that it coasted to a stop at an altitude of 1,000 feet, turned over, detected the target with its IR sensor, and glided to impact. For reasons unknown to the panel, HOMINE was dropped before reaching service use.

It may be wise, however, for the Marines to examine the HOMINE concept with an eye toward further miniaturizing both the sensor and the kill system using modern technology. A variety of such broad-coverage systems that place little weight on the logistic burden is possible.

Far-term Needs and Recommendations

Mine Delivery

Any consideration of the future emphasis that should be placed on mines is incomplete without considering the deliverability of such weapons. Today, virtually all of our mines are delivered by either submarines or aircraft. U.S. forces have no surface ships uniquely configured for mine laying, and for a very good reason. The advantage of such ships diminished as the transition was made from the cumbersome Mk-6 type moored mines that had to be trundled around on their own wheels to the more easily handled bottom influence mines and more efficiently designed moored mines. Most modern mines can be laid by practically any surface ship, as demonstrated by the former Soviet Union and by such countries as North Korea, Iran, and Iraq. The Navy’s lack of attention to surface ship mine laying has been due primarily to the fact that the emphasis has been on offensive rather than defensive mining, where the advantage of the surface ship and its delivery capacity are greater. Let us assume, then, that the Navy’s emphasis in mine laying will continue to be on the submarine and aircraft and that the surface ship can be pressed into service without undue modification.

The main advances in mine deliverability will come from the mines themselves, not from new aircraft and submarine designs. Specifically, advances will come from the continued miniaturization of electronics and from the introduction of explosives with greater energy yield. As an example, the old Mk-55 mine was 21 inches in diameter and 114.6 inches long (the instrument section took up about 20 percent of this length), weighed 2,196.5 pounds, and carried a 1,270-pound explosive charge. Using modern electronics and case material and merely doubling explosive energy yield (considered attainable during the projection period of this study) would produce a mine with improved performance and equivalent destructive capacity, but that would be only around 45 inches in length and would weigh about 700 pounds. Thus, it appears possible, without heroic efforts, to cut the mine delivery sortie requirements of both submarines and aircraft by more than half. Also, if the tubes on a retiring SSBN could be used for mine laying (now being considered for the Tomahawk missile) each D-5 tube could carry roughly 35 mines, or a total of 840. Such a size and weight reduction also introduces the possibility of the delivery of sea mines by rocket, which is now done with land mines.

Networked, Controllable Minefield

With the projected advances in sensors, processing, and communications technologies, an advanced concept of an intelligent minefield appears feasible for the future generation of sea mines. Envisioned is a networked laydown of individual mines that can communicate to pass information and data and to utilize effectively the distributed sensor information they collectively obtain. In addition to the increased performance obtainable from distributed surveillance, the minefield could be designed with sufficient intelligence to achieve remote fail-safe command and control and selective targeting. This attribute could reduce the current aversion to mining conceived as a distribution of indiscriminate lethal weapons.

The networked minefield concept includes the notion of separated detection or targeting sensors and attack weapons. This would permit the cost-effective laydown of separate detection nodes and connected weapons tailored to the requirements of the local environment and threat picture. The technology enablers for multi-influence detection sensors—distributed processing, networked communications, intelligent control architectures, and lethal attack mechanisms—should be pursued. The networked, controllable minefield has the potential to mitigate concerns regarding indiscriminate mining and has the flexibility for tailored deployment that can provide significant cost savings.

CROSS-CUTTING TECHNOLOGIES

This section deals with several technologies that are applicable to a wide spectrum of mine warfare and mine countermeasures issues.

Modeling and Simulation for Mine Warfare

The Navy and Marine Corps, as well as the other Services and DOD, are becoming increasingly dependent on the rapidly expanding field for the design of weapons and their countermeasures, for their evaluation, for the development of tactics and doctrine, for training, and as an aid in procurement decisions. This subject area is comprehensively addressed by the Panel on Modeling and Simulation in *Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force, Volume 9: Modeling and Simulation*. As with any application of modeling and simulation, modeling and simulation aids for mine warfare should rest on a sound theoretical basis. Unfortunately, developing such a basis is not straightforward because the underlying mathematics are difficult and require an understanding of probabalistic dependencies. In the past, workers have developed models for estimating the effects of minefields or mine countermeasures that, although seemingly sound, have in fact been highly misleading (see Appendix J, “Probabilistic Dependencies in Combat Models,” in *Volume 9: Modeling and Simulation*).

Configural Theory

Configural theory, developed by a small research group working under contract for the Navy, is a mathematical theory that quantifies the relationships between the behavior of weapons in use in combat and their individual characteristics. Its principal purpose is to provide concepts and mathematical relationships to improve understanding of the behavior of weapons in combat and of their combat effectiveness. Its name is derived from its central concept, configuration, which is the mathematical expression of the fact that the disposition in space and time of the targets and weapons of the attacker and defender influences the outcome of the engagement and the combat effectiveness of those weapons. Among the conclusions from the research[17,18] conducted thus far are the following: (1) nonconfigural representation of target-weapon encounters may be suffi-

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[17] Horrigan, Timothy, J. 1992. “The Configuration Problem and Challenges for Aggregation,” pp. 102-153 in *Proceedings of the Conference on Variable-Resolution Modeling*, Washington, D.C., May 5-6, CF-103-DARPA, Paul K. Davis and Richard Hillestad, eds., National Defense Research Institute, RAND Corporation, Santa Monica, Calif.

[18] Horrigan defines configural theory as “a mathematical theory for quantifying the relationships between the behavior of weapons in use in combat and their individual characteristics. Its principal purpose is to provide concepts and mathematical relationships to improve our understanding both of weapon behavior in combat and of combat effectiveness. Its name is derived from its central concept, configuration, which is the mathematical expression of the fact that the disposition in space and time of the targets and weapons of the attacker and the defender is inseparable from the outcome of the engagement and the combat effectiveness of those weapons.”

cient to invalidate a model or simulation; (2) Lanchester-theory-based representations, deterministic or stochastic, are generally nonconfigural; (3) the conception of weapons effectiveness and the derivative mathematical models, particularly those based on initial threat and free encounter (independent event), may be inappropriate; and (4) nonconfigural assessments may, in some instances, significantly overstate weapon effectiveness and make less effective weapons appear preferable to more effective weapons.

Configural theory is an approach to mine warfare analysis that permits development of a comprehensive and reasonably correct model system encompassing relevant characteristics and interactions, including spatial, temporal, and entity-specific relationships. It has generated a new family of meaningful measures of effectiveness. Simpler analytical models that form the basis of tactical decision aids currently in use for mine warfare applications do not properly account for probabilistic dependencies and entity-specific relationships (see, for example, Appendix J in *Volume 9: Modeling and Simulation* in this nine-volume series). Not surprisingly, the application of configural theory requires greater rigor and time than nonconfigural models, but its use would enable a significantly better understanding of mine warfare and thus help to optimize the allocation and application of mine warfare resources.

New Modeling and Simulation Tools

Advances in computer memory, processing power, networking, and visualization have dramatically improved modeling and simulation capabilities. These technologies offer revolutionary advances in the simulation of military operations and high-detail interactive representations for design and manufacture. Organizations involved with traditional exercises, training simulators, computer simulations, war games, system design, and test and evaluation are beginning to experiment with these new tools. Two key issues are how much to invest and where. A key concern is verification, validation, and accreditation (VV&A).

The key benefits of the new modeling and simulation technologies are bringing the operator into the simulation and providing necessary linkages such as those between designers and operators, different members of a unit, different units of a force, and so forth. For the MCM community, four key applications are possible: (1) integrating MCM into Navy and Joint Force planning for acquisition and operations; (2) improved tactical development and training despite geographic separation of the principal MCM forces from the fleet and dispersal of the reserve component; (3) the timely development of appropriate systems to counter a threat that is rapidly changing, increasingly sophisticated, affordable to all potential enemies, and likely to be encountered in difficult coastal environments; and (4) improved understanding of the environments relevant to MCM in the littorals.

The key challenges to realizing the promise of the new modeling and simulation tools for MCM are the selection of appropriate focal points for investment, adapting emerging technologies to these focal points, acquiring supporting databases, and designing a VV&A program that will build confidence in the tools and establish their effectiveness.

Environmental Characterization

The effectiveness of MCM sensors is critically dependent on the environment in which they operate. LIDARs, for example, are ineffective in dust storms. Sonars operate differently in fresh and saline waters or in regions with hard and soft bottoms. Knowing the environment in which the sensor is operating and understanding its effects on the sensor can make significant differences in levels of performance. MCM forces need to be provided with a level of environmental prediction and sensing and an ability to optimally tune their systems, not unlike those provided to ASW forces. Adaptive sensors, which automatically sense their most effective parameters, can provide the needed in situ data. In the case of sonar, for example, the system itself can be used to measure its surrounding environment—sound speed profile, bottom backscatter, surface roughness, bubble attenuation, and so on—and automatically select an optimal operating frequency, beam pattern and signal type.

Global Positioning System

To neutralize the mine threat in minimum time, with minimum assets and effort, will require that all surface and air MCM platforms and those platforms transiting cleared channels be equipped with GPS receivers, that crews be thoroughly trained and practiced in their use, and that all charts and maps be digitized using GPS coordinates. The spatial coordination required by the MCM-amphibious assault-sea-based support element, from crisis initiation to last mine cleared, is demanding, and can be achieved only if GPS precision is available to all components. Without it, the goal of rapid conflict resolution with minimum casualties will not be attained. The panel urges the Navy and Marine Corps to equip all relevant platforms, subject their crews to extensive training, and ensure the conversion of maps and charts.

MCM Night Operations

The MCM platforms available in any future conflict could effectively be doubled simply by adding the capability to carry out night operations. The panel is aware of the principal reasons such operations have not already become standard practice. AMCM helicopters are not equipped with artificial horizons and night vision equipment, and while in tow, they fly in a dangerous part of the flight envelope. MCM surface ships are justifiably concerned about navigation in close proximity to the minefield and about the possibility of floating mines. The provision of artificial horizons and night vision equipment has a straightforward fix, and systems have been recommended above for dealing with the floating mine problem. The question of night flying in tow with acceptable safety given proper equipment, the panel leaves to helicopter pilots to judge. Otherwise, the panel sees no reason why the MCM force should not adopt—even eventually prefer, all things considered—night operations. This is but another way of leveraging the force.

RECOMMENDATIONS

Mine warfare continues to be a technological challenge because of the proliferation of mines and mine technology. However, the Navy can take steps now that will provide a robust countermine capability within the horizon of this study (2035), enabling the United States to execute national policy worldwide. Recommendations arising from this study, and detailed in the report, are summarized below.

Highest-level Recommendations

Near Term

- Implement a factory-to-seabed intelligence, surveillance, and reconnaissance capability, using a full set of ISR methods, including surveillance by satellite, atmospheric and undersea manned and unmanned vehicles, submarines, human intelligence assets, and special forces.
- Develop technologies that will provide naval forces with organic MCM capability, including helicopter-compatible sweeping and hunting equipment, remotely operated off-board surface or UUV sensors, and on-board MCM sonars.
- Aggressively pursue the development of so-called brute force technologies that will neutralize mines and obstacles in the very shallow water zone, the surf zone, and the craft landing zone.

Far Term

- Develop technologies for advanced networked sensor and weapon systems consisting of the following:
  - — Autonomous and semiautonomous networked undersea systems using small, autonomous undersea vehicles, bottom-crawling variants, and fixed sensors for far-forward covert MCM; and
  - — Controllable mines with remote fail-safe command and control (C^2) and selective targeting.
- Develop next-generation MCM ships as small platforms capable of sea state 4 operation, carried by a mother ship capable of battle group speeds. De-

velop the lightweight hunting and sweeping technologies required for these smaller units.

- Apply reasonable mine shock hardening and effective acoustic and magnetic signature reduction technologies to all new-construction ships.

Recommendations for Follow-on Action

- Build an expendable mine neutralization system capable of being used, with minimal adjustment, by AMCM helicopters, by the MCM-1 and MHC-51 MCM ships, and by small MCM surface craft yet to be introduced.
- Continue research to reveal the acoustic detection and classification methods used by dolphins. Emulate this capability to radically improve sonar sensor performance.
- Continue to develop synthetic aperture sonar technologies to significantly improve the location and classification of mines from a safe distance.
- Establish a research and demonstration program for rigid polyurethane foam causeway concepts.
- Support the development of mechanical methods—ploughs, chains, and power blades.
- Develop guinea pig ships and barges to verify clear paths to the beach. Consider unmanned, precisely navigated, hardened platforms.
- Specifically test precision bombing techniques for removal of mines in shallow water and in the surf and craft landing zones. Investigate this technique in light of newly developing higher-yield explosives.
- Support further development of explosive MCM methods such as net and line charges.
- Support research on pulse power technologies; this should include demonstration of concept and performance measurements.
- Take full advantage of new modeling and simulation tools with initial focus on fleet-level applications, training, exercises, decision aids, and tactical development.
- Reinvigorate the mine design team to provide effective offensive mining concepts and exploit threat mines.
- Continue to develop technologies to improve environmental characterization for improved sensor performance, including through-the-sensor environmental measurement methods.
- Provide systems and training that will allow the fleet to conduct night MCM operations.

APPENDIXES

A

Terms of Reference

CHIEF OF NAVAL OPERATIONS

28 November 1995

Dear Dr. Alberts,

In 1986, at the request of this office, the Academy's Naval Studies Board undertook a study entitled "Implications of Advancing Technology for Naval Warfare in the Twenty-First Century." The Navy-21 report, as it came to be called, projected the impact of evolving technologies on naval warfare out to the year 2035, and has been of significant value to naval planning over the intervening years. However, as was generally agreed at the time, the Navy and Marine Corps would derive maximum benefit from a periodic comprehensive review of the implications of advancing technology on future Navy and Marine Corps capabilities. In other words, at intervals of about ten years, the findings should be adjusted for unanticipated changes in technology, naval strategy, or national security requirements. In view of the momentous changes that have since taken place, particularly with national security requirements in the aftermath of the Cold War, I request that the Naval Studies Board immediately undertake a major review and revision of the earlier Navy-21 findings.

The attached Terms of Reference, developed in consultation between my staff and the Chairman and Director of the Naval Studies Board, indicate those topics which I believe should receive special attention. If you agree to accept this request, I would appreciate the results of the effort in 18 months.

Sincerely,

J. M. BOORDA
Admiral, U.S. Navy

Dr. Bruce M. Alberts
President
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

NATIONAL ACADEMY OF SCIENCES
DEC 01 1995
OFFICE OF THE PRESIDENT

Enclosure

TERMS OF REFERENCE

TECHNOLOGY FOR THE FUTURE NAVY

The Navy-21 study (Implications of Advancing Technology for Naval Warfare in the Twenty-First Century), initiated in 1986 and published in 1988, projected the impact of technology on the form and capability of the Navy to the year 2035. In view of the fundamental national and international changes -- especially the Cold War's end -- that have occurred since 1988, it is timely to conduct a comprehensive review of the Navy-21 findings, and recast them, where needed, to reflect known and anticipated changes in the threat, naval missions, force levels, budget, manpower, as well as present or anticipated technical developments capable of providing cost effective leverage in an austere environment. Drawing upon its subsequent studies where appropriate, including the subpanel review in 1992 of the prior Navy-21 study, the Naval Studies Board is requested to undertake immediately a comprehensive review and update of its 1988 findings. In addition to identifying present and emerging technologies that relate to the full breadth of Navy and Marine Corps mission capabilities, specific attention also will be directed to reviewing and projecting developments and needs related to the following: (1) information warfare, electronic warfare, and the use of surveillance assets; (2) mine warfare and submarine warfare; (3) Navy and Marine Corps weaponry in the context of effectiveness on target; (4) issues in caring for and maximizing effectiveness of Navy and Marine Corps human resources. Specific attention should be directed, but not confined to, the following issues:

1. Recognizing the need to obtain maximum leverage from Navy and Marine Corps capital assets within existing and planned budgets, the review should place emphasis on surveying present and emerging technical opportunities to advance Navy and Marine Corps capabilities within these constraints. The review should include key military and civilian technologies that can affect Navy and Marine Corps future operations. This technical assessment should evaluate which science and technology research must be maintained in naval research laboratories as core requirements versus what research commercial industry can be relied upon to develop.

2. Information warfare, electronic warfare and the exploitation of surveillance assets, both through military and commercial developments, should receive special attention in the

review. The efforts should concentrate on information warfare, especially defensive measures that affordably provide the best capability.

3. Mine warfare and submarine warfare are two serious threats to future naval missions that can be anticipated with confidence, and should be treated accordingly in the review. This should include both new considerations, such as increased emphasis on shallow water operations, and current and future problems resident in projected worldwide undersea capability.

4. Technologies that may advance cruise and tactical ballistic missile defense and offensive capabilities beyond current system approaches should be examined. Counters to conventional, bacteriological, chemical and nuclear warheads should receive special attention.

5. The full range of Navy and Marine Corps weaponry should be reviewed in the light of new technologies to generate new and improved capabilities (for example, improved targeting and target recognition).

6. Navy and Marine Corps platforms, including propulsion systems, should be evaluated for suitability to future missions and operating environments. For example, compliance with environmental issues is becoming increasingly expensive for the naval service and affects operations. The review should take known issues into account, and anticipate those likely to affect the Navy and Marine Corps in the future.

7. In the future, Navy and Marine Corps personnel may be called upon to serve in non-traditional environments, and face new types of threats. Application of new technologies to the Navy's medical and health care delivery systems should be assessed with these factors, as well as joint and coalition operations, reduced force and manpower levels, and the adequacy of specialized training in mind.

8. Efficient and effective use of personnel will be of critical importance. The impact of new technologies on personnel issues, such as education and training, recruitment, retention and motivation, and the efficient marriage of personnel and machines should be addressed in the review. A review of past practices in education and training would provide a useful adjunct.

9. Housing, barracks, MWR facilities, commissaries, child care, etc. are all part of the Quality of Life (QOL) of naval personnel. The study should evaluate how technology can be used to enhance QOL and should define militarily meaningful measures of effectiveness (for example, the impact on Navy readiness).

10. The naval service is increasingly dependent upon modeling and simulation. The study should review the overall architecture of models and simulation in the DoD (DoN, JCS, and OSD), the ability of models to represent real world situations, and their merits as tools upon which to make technical and force composition decisions.

The study should take 18 months and produce a single-volume overview report supported by task group reports (published either separately or as a single volume). Task group reports should be published as soon as completed to facilitate incorporation into the DoN planning and programming process. An overview briefing also should be produced that summarizes the contents of the overview report, including the major findings, conclusions, and recommendations.

B

The Submarine Capability of Other Nations

Box B.1 lists the current submarine capabilities of nations worldwide. In the future, submarines can potentially be a serious threat to U.S. power projection forces (see Box B.2). The United States may face a spectrum of force levels and capabilities of submarines. Examples include the following:

- *Russia*. Many, including very capable nuclear-powered submarines operating worldwide, potentially challenging the United States in every corner of the globe.
- *China*. Many, some of which could be advanced-technology submarines operating up to 2,500 km from the Chinese coast, capable of challenging the United States in the western Pacific (China has committed to three new submarine development programs: SS, SSN, and SSBN).
- *Iran*. A few medium-technology submarines operating in the Persian Gulf, Strait of Hormuz, and the Arabian Sea, challenging the right of passage of ships.
- *Korea*. Many medium- and low-technology submarines operating essentially as a distributed, smart minefield preventing operation of U.S. naval forces in waters contiguous to both North and South Korea.

BOX B.1 Current Operational Submarines (Estimates as of January 1997)

Russia	120	(77 nuclear, 43 diesel)
China	70	(6 nuclear, 64 diesel)
North Korea	40	
Germany	17	
France	17	(11 nuclear, 6 diesel)
India	18	
Turkey	16	
Japan	16	
United Kingdom	14	(all nuclear)
Norway	12	
Sweden	9	
Italy	9	
Greece	8	
Peru	8	
Spain	8	
Pakistan	6	
South Korea	8	
Denmark	5	
Brazil	5	
Yugoslavia	3	
Netherlands	4	
Egypt	4	
Argentina	4	
Chile	4	
Taiwan	4	
Australia	3	
Canada	3	
Israel	3	
Poland	3	
Portugal	3	
South Africa	3	
Bulgaria	2	
Albania	2	
Columbia	2	
Ecuador	2	
Indonesia	2	
Iran	3	
Venezuela	2	
Algeria	2	
Romania	1	
Singapore	1	

NOTE: All submarines are diesel unless specified.

BOX B.2 Submarines on Order or Under Construction, January 1997

Australia	1 COLLINS Class SS in trials, 4 more U/C or on order
Brazil	1 Type 209 SS fitting out, 1 U/C; 1 enlarged Type 209 on order
China	1 or more SONG U/C; 1 Type 094 SSBN possibly U/C
France	1 LE TRIOMPHANT SSBN U/C; 1 AGOSTA-90B SS U/C for Pakistan
Germany	4 Type 212 SS on order; 1 Type 800 SS on trials and 2 U/C for Israel
India	2 Type 209/1500 SS projected, if funding provided
Italy	2 Type 212 SS authorized (to deliver 2003, 2005)
Japan	1 HARUSHIO SS fitting out, 1 OYASHIO SS fitting out, 3 more authorized or U/C
Korea, North	Estimated up to 6 SANGO SSC U/C or fitting out
Korea, South	1 Type 209/1200 SS fitting out, 2 U/C
Pakistan	2 AGOSTA-90B on order (1 to have hull built in France for fitting out in Pakistan)
Russia	1 BOREY SSBN U/C, 1 OSCAR-II SSGN U/C, 1 SEVERODVINSK SSN U/C; 4 AKULA-II SSN U/C, 2 PROJECT 636 KILO SS U/C for China, 1 PROJECT 677 AMUR SS on order (private, for lease to Russian Navy)
Sweden	2 GOTLAND SS fitting out
Turkey	2 Type 209/1400 U/C
United Kingdom	1 VANGUARD SSBN U/C
United States	1 OHIO SSBN fitting out, 1 SEAWOLF SSN in trials, 2 SEAWOLF SSN U/C, 4 NSSN SSN authorized

C

Mine Warfare and Mine Countermeasures—Current Status

As stated in the main text of this report, current MCM forces are designed primarily for a Cold War scenario. Specifically, the MCM force was designed to enable port breakout, to counter relatively deep ASW mines, and to counter mines in straits, choke points, and the outer continental shelf that might be used to impede the flow of logistics to Europe or, to a lesser extent, the western Pacific. Defense planners left to allies the task of clearing mines in the shallow-water approaches to their ports and their near-shore transit routes. It should also be recalled that the current U.S. capability was designed during that period when "we never have to engage in another opposed amphibious assault" was the conventional wisdom. Now the United States is faced with a situation in which breakout from its own ports has, for the time being at least, lost importance and the threat of deep-water mining has diminished. Breakout from advanced points for prepositioning ships, however, is important. Moreover, conducting an opposed amphibious assault is once again a very real possibility, and regional allies may not be available to clear shallow-water approaches to logistical support offloading sites and landing areas. The United States cannot be sure that it will have the MCM assistance of coalition forces as it did during the Persian Gulf War.

The Navy's current MCM capability includes the following major systems:

- MCS-12 mine countermeasures command, control, and support ship USS *Inchon* (LPH-12). Equipped with a modern C^4I system, the *Inchon* will provide full mission planning and execution and evaluation capabilities to support an MCM squadron commander and staff, as well as support for airborne mine countermeasures, explosive ordnance disposal, MCM detachments, and surface mine countermeasures ships.

- The Avenger-class MCM-1 ship capable of mine sweeping, mine hunting, and mine neutralization: the MCM-1 carries the AN/SQQ-30 (AN/SQQ-32 on later ships of the class) variable-depth mine hunting sonar and the AN/SLQ-48 mine neutralization vehicle.
- The Osprey-class MHC-51 coastal mine hunter equipped with the AN/SQQ-32 variable-depth mine hunting sonar and the AN/SLQ-48 mine neutralization vehicle.
- The MH-53E Sea Stallion MCM helicopter capable of sweeping mechanical (Mk-103) and influence (Mk-104/105/106, AN/SPU-1 Orange Pipe) mines and mine hunting (AN/AQS-14).
- Explosive ordnance disposal (EOD) and special forces (i.e., SEALs capable of mine intelligence, reconnaissance, and the placement of neutralization charges).
- The Mk-4 (moored mine hunting), Mk-5 (mine recovery), Mk-6 (swimmer defense), and Mk-7 (bottom mine hunting) mammal systems. These systems are capable of detecting buried mines and placing neutralization charges on moored, bottom, and buried mines.

At present, no other country can match the MCM capability resident in these six systems. Although countries such as Japan, the United Kingdom, France, Italy, Germany, the Netherlands, and Belgium have a respectable MCM capability, none have airborne MCM, nor do they have mammal systems with their unique mine hunting and mine neutralization capabilities. This is not to say, however, that the U.S. Navy's existing systems represent a balanced, trouble-free capability. The Italian nonmagnetic Isotta-Fraschini diesel engines, which are the main power systems aboard the MCM-1 and MHC-51, have experienced the "teething" problems expected of any new design. Limited to speeds of 13.5 and 15 knots, respectively, these ships cannot deploy with the battle group and must be forward deployed or transported to a crisis site by heavy-lift ship as was done in the Persian Gulf War.

The AN/SLQ-48 mine neutralization vehicle used by both the MCM-1 and the MHC-51 is not well suited to the neutralization of shallow-water mines. The vehicle tends to be underpowered and may leave on the bottom a mine that looks like a mine to any subsequent sonar search and an explosive charge subject to later detonation under proper impact conditions. Although the MH-53E MCM helicopter has mine hunting capability, it does not yet include a neutralization component and the helicopters are not equipped with GPS receivers. Further, MH-53Es are not equipped with artificial horizon and night vision equipment and are thus incapable of night operations.

SYSTEMS UNDER DEVELOPMENT

The primary MCM systems currently being developed are included within the scope of the Joint Countermine Advanced Concepts Technology Demonstration Phases I and II. Although additional concepts currently are being considered for Phase III ACTD, this phase has not yet been authorized.

Joint Countermine ACTD

Over the years the problem with advancing the capability of U.S. MCM forces has not been the lack of good ideas or the lack of a technically skilled research team. During the Cold War years, many excellent and needed technical advancements entered the research and development program, but few emerged. In many of these cases the project was canceled not because the concept was found to fall short of expectations but because funding support was diverted to other weapons or countermeasures projects that were considered more important. Additionally, there has been too little attention to viewing MCM forces as a total system in which operational requirements needed for a balanced capability are recognized, technical solutions (frequently already in the R&D program) are identified, and program components are protected until they reach service use. The recently introduced ACTD program offers a solution to both of these problems.

The ACTD is a joint effort in which each service with a stake in a given warfare area, or component of an area, submits for competition those of its concepts already elevated to the status of advanced technology demonstration (ATD). The ATDs chosen for an ACTD are those that can be brought to the prototype stage for performance demonstration, or adequately modeled for such, in the near term—usually two to five years. The performance of the concept is evaluated in an exercise, and the results are used to reach a decision on acceptance or rejection. At a minimum, the fleet is left with a useful prototype from among the accepted concepts.

The Joint Countermine ACTD now in effect consists of concepts submitted by the Army, Navy, and Marine Corps and covers sea mines, very shallow water mines and obstacles in the surf zone and the craft landing zone, and inland land mines. The officially accepted Joint Countermine ACTD consists of 12 MCM concepts broken down into two phases for demonstration before the end of this decade. It should be pointed out that due, in part, to the limitation on the number of concepts accepted for a given phase, the ACTD does not represent, in full, those concepts required to produce a balanced MCM capability up to the craft landing zone for the Navy-Marine Corps team. The MCM concepts accepted into Phases I and II of the Joint Countermine ACTD are identified and described briefly below.

Joint Countermine ACTD Phase I

- *Littoral remote sensing (Generation One).* Also called Radiant Clear, this concept aims at the fusion of surveillance data obtained from national assets and from theater, tactical, civilian, and commercial sensors to provide information on mine movement from bunker to mine layer to minefield, including the mining and fortification of beaches and very shallow water.
- *Dolphin-towed advanced sensors.* Now known as the Remote Minehunting Operational Prototype (RMOP), this proof-of-concept-only program utilizes a forward-looking and towed side-scan sonar aboard the Dolphin semisubmersible vehicle to detect and classify mines from deep to shallow water. Utilized in a semicovert minefield reconnaissance role, RMOP is radio controlled, utilizes GPS navigation, transmits its data in real time, and is to be transported, launched, operated, and recovered by a Navy combatant.
- *Magic Lantern (Adaptation), or ML(A).* ML(A) is a helicopter-mounted laser system for the detection of mines in shallow water, in very shallow water, on the beach, and inland. This is a joint Army, Navy, Marine Corps version that is not intended to detect moored and floating mines in deeper water.
- *Coastal battlefield reconnaissance and analysis (COBRA).* COBRA utilizes a UAV platform equipped with multispectral video sensors for mine and obstacle detection and a forward-looking video for battlefield surveillance to provide a surveillance and reconnaissance capability for detecting mines and obstacles in the SZ, in the CLZ, and inland. A ground station link provides real-time mission assessment and postprocessing of data for minefield and obstacle identification.
- *Airborne standoff minefield detection system (ASTAMID).* This Army system is similar to the Marine Corps COBRA mine detection system in that it is mounted on a UAV. Rather than a multispectral video sensor, however, ASTAMID uses an IR sensor to detect the thermal contrast between a proud land mine and the surrounding ground, or between disturbed and undisturbed ground in the case of buried mines.
- *Explosive neutralization.* There are two different methods: (1) SABRE, a rocket-propelled line charge that is fired out ahead of an LCAC or other type of craft and (2) a distributed explosive array net that contains shaped explosive charges at its nodes and is projected ahead of an LCAC to neutralize mines in the surf zone and the craft landing zone.
- *Joint amphibious mine countermeasures (JAMC).* JAMC is a Marine Corps program that is intended to clear mines and obstacles from the high-water mark through the craft landing zone by dragging a heavy chain between two D-7 bulldozers using plows to clear their own path.
- *Army classified program.* This classified Army program is intended to provide standoff neutralization of metallic and nonmetallic land mines.
- *Close-in Man-portable Mine Detector (CIMMD).* This Army ATD is

intended to improve the present hand-held mine detection system by making it sensitive to both metallic and nonmetallic mines.

- *Off-route Smart Mine Clearance (ORSMC).* This Army system utilizes a HUMVEE modified for low observability to serve as a decoy or guinea pig against smart mines designed to deliver a projectile against armored vehicles.

Joint Countermine ACTD Phase II

The following naval systems will be included in Phase II:

- *Near-term mine reconnaissance system.* The NMRS is a 21-inch-diameter torpedo-shaped UUV to be deployed, controlled, and recovered via fiber-optic link from a submarine. Its purpose is to serve as a covert minefield reconnaissance vehicle capable of transmitting its data in real time.
- *Littoral remote sensing (Generation Two).* Includes several advancements over Generation One, particularly with respect to the fusion of data from material assets.
- *Advanced Lightweight Influence Sweep System (ALISS).* The ALISS concept utilizes advanced acoustic and magnetic techniques to sweep influence mines.
- *UUV advanced sensors.* This ATD emphasizes advanced sensors developed for use by a 21-inch-diameter UUV. The sensors consist of a toroidal volume search sonar, a side-looking sonar, a synthetic aperture sonar, and a superconducting quantum interference device (SQUID) magnetic sensor.

D

Compliance with Laws and Policy Protecting Marine Mammals and Endangered Marine Species

An issue of critical importance to today's Navy, and almost certainly to be important to 21st-century forces, is the growing concern about the possible harmful effects of naval operations on marine life. The perceived impact might ultimately restrict operations and limit the use of both sonar systems and small underwater explosives (as little as 4 pounds of explosives). The ocean is a very efficient medium for sound propagation, especially at low frequencies. Even low-intensity sounds can propagate to very long ranges, so that the areas over which marine life might be affected—and therefore the size of the potentially affected marine populations—can be enormous.

Early in 1997, the Commander in Chief of the Atlantic Fleet took unprecedented action to change a major North Atlantic Treaty Organization (NATO) operation being held in the Atlantic off the coasts of Georgia and Florida. Three northern right whales had been found dead in the Atlantic. The cause of the deaths of these animals was never determined, but the impact of their deaths generated enough public interest that the White House became involved and the Navy was ultimately forced to drastically curtail the exercise.

The levels of low-frequency ambient sound in almost all the world's oceans are already dominated by anthropogenic sources, primarily shipping noise. It has been estimated that the background sound level at 100 Hz has been increasing by about 1.5 dB per decade since the advent of propeller-driven ships. Impulsive sounds from air guns or from seismic, oil, and gas exploration are also major contributors to the low-frequency background noise level. High- and mid-frequency Navy tactical and weapon sonars produce more localized disturbance, but the sound from new low-frequency ASW sonars can reach very long distances.

Navy weapon tests and ship shock tests generate very high intensity sounds. All of these factors have the potential to interfere with marine mammals.

The issue is primarily legal as well as humanitarian. The United States has enacted a body of laws and is signatory to international agreements designed to protect marine mammals and endangered species. Protection ranges from outright bans on hunting and harvesting to more subtle prohibitions of those actions that might disturb, harass, or "take" these animals. Harassment and takes, as used here, are legal terms that are sometimes interpreted to include any activity that alters the animal's behavior in even minor ways. Behavioral modification, something as innocent as simply causing an animal to change swimming direction, is within the legal definition of take. To harass, to take, is unlawful without a permit.

Under present law, the preparation of detailed environmental impact statements is usually required by the National Environmental Policy Act to assess the potential for a significant environmental effect or the possibility of a take. Even for small-scale operations and experiments, these documents are costly to prepare and can take up to a year to complete.

"Take permits," permission to harass a small number of marine mammals from certain Navy at-sea experiments and operations, are also frequently required. Permits can take more than a year to process before they are granted, if they are granted at all. In some cases, elaborate environmental surveys and observations are required prior to and during the test period. Acoustic monitoring for the presence of marine mammals and for ascertaining the impact of the operation or test on the mammal or its habitat is also usually required. Compliance with the laws protecting marine mammals is expensive, time consuming, and potentially devastating to a Navy program. It can, and has, stopped programs cold.

Unfortunately, the underlying scientific understanding of the effects of sound on marine life, upon which to base reasonable strategies for ensuring that these laws are not violated and that marine life is protected, does not exist. As a consequence, decisions to issue the required permits either are arbitrary or are based on very limited data and frequently incorrect assumptions. For example, the safe level of exposure to underwater acoustic energy being proposed by some is 130 dB at 1 micropascal (about 65 microwatts), a value based on a single experiment involving bowhead whales.

This was the level at which 50 percent of migrating whales observed over a few days altered course to swim around an oil tower equipped with an underwater transmitter that emitted drilling-type noise. Whale tracks were altered by only a few degrees, and most whales resumed their original course after passing the tower. Whether this affected the whales in any negative way, both for the near term and over the long term, is unknown. Whether it was anything more than an indication of hearing sensitivity is also unknown. Whether other species would react differently is unknown. Whether this event would occur at a different geographic location is likewise unknown. Whether the signal type, frequency, intensity, duty cycle, or bandwidth are factors is unknown. The sensitivity of marine mammals to sonar sounds and effects of sonar sounds on these mammals simply are not known.

Further, in contrast to the 130-dB level, surface ships generate from 5 to 100 watts of acoustic noise, about 175 to 190 dB. Large cruise ships can generate levels of more than 200 dB. Blue whales themselves have been observed to generate signals of nearly 190 dB.

The laws are not restricted to marine mammals. The Endangered Species Act similarly protects other living marine resources. In some cases, such as that of the endangered sea turtle, for example, we do not even know the range of the animal's hearing, and we certainly do not know the threshold of its pain or the disturbance caused by underwater acoustic energy. Some endangered sea birds can dive into depths of more than 500 feet and therefore be subjected to underwater acoustic noise. Little is known of their hearing underwater or the potential damage due to the exposure.

In the case of marine mammals they are known to emit sounds in the frequency band of Navy sonars, and it has been conjectured that they use these vocalizations for navigating, hunting for food, locating potential mates, and perhaps even general communications. The issue is whether or not, and to what extent, naval activities that generate underwater sound interfere with these functions.

There is also concern about the effects of underwater sounds on people, both commercial and recreational divers, for example. Here too a safe exposure limit is being discussed, based on a single experiment. The problem has intensified lately, primarily as the result of an increasingly aware, vocal, and powerful environmental activist movement that is demanding rigid compliance with the laws protecting marine mammals and endangered marine species. The situation has been exacerbated by the Navy's low-frequency active acoustic ASW development programs, which are based on very high intensity sonars operating in the vocalization frequency bands of many marine mammals, especially baleen whales. As noted above, these low-frequency sonar signals are capable of very long range propagation.

The Navy's development of low-frequency sonars is a result of the steady, historical reduction in submarine-radiated noise in all submarine variants—nuclear, diesel, and air independent—which has reduced the effectiveness of passive ASW and spurred the development of active methods. It is anticipated that over the next several decades, the proliferation of quiet, capable, and effective submarines through foreign sales and indigenous manufacture will result in even more reliance on active acoustics, so that the issue of compliance with environmental law will almost certainly be a major future problem for the Navy unless mitigation measures are undertaken.

The Navy has had to seek permits from the National Marine Fisheries Service, and in some cases the Department of the Interior, to conduct ship-shock tests (using explosive sources) and tests of prototype sonar systems, as well as exercises to develop tactics and strategies for employing LFA sonars. Weapon testing in the Gulf of Mexico has been constrained by environmental compliance. The Navy has had to prepare extensive and expensive environmental assessments and environmental impact statements for these operations and, in some instances, to alter venues and test plans.

In almost all cases, regulatory decisions have been based on either anecdotal or, at best, limited scientific data and understanding. The compliance impact on a Navy operation or experiment can be debilitating. The legal costs for obtaining permission to undertake DDG 53 ship-shock tests are estimated to be $1.5 million. The tests themselves were delayed by two months following a court injunction. The cost of the delays added $3 million to the program.

Similarly, tests of the LFA sonar system have been restricted to certain areas and limited to certain power levels. For environmental compliance, operational use of the SSQ 110 sonar system is highly restricted, both in geographic area and in mode of operation. Although the primary concern has focused on the use of low-frequency sonars and the acoustic energy from underwater explosions, there is an awareness that even tactical sonars interfere with many marine species. Almost nothing is known about the effects of mid-frequency, tactical sonars on marine mammals and endangered marine species.

Because there is no immediate, identified threat to national security, it is unrealistic to appeal for a waiver to these environmental laws based on national security needs. Also, because environmental responsibility is an increasingly universal concern, it is entirely possible that the Navy will be prevented from developing and fielding many underwater acoustic systems required by its future missions. The health and survivability of marine life are a grave concern. The Navy has ensured its rightful role as a proper steward of ocean resources, but this role is now at odds with the full use of its own resources in the ocean environment.

The Navy must comply with U.S. law and policy that safeguards the health and well-being of marine animals, but the thresholds for determining the overall health and well-being should be based on sound science.

The Navy, singularly, is in a position to address this pressing national issue. Many years ago, the Navy took the lead; it now has several trained animals and has developed the technology to determine the impact of Navy operations on marine mammals and endangered marine species. Also, the Navy has a unique capability to understand the detailed propagation of underwater acoustics and therefore can ultimately ascertain the potential impacts of underwater sound on marine life.

The United States has led the world in developing a legal framework for ensuring that endangered marine species are protected. It is a signatory to international agreements to limit whaling, and U.S. national laws are exemplary. It is important that this conflict between responsible environmental stewardship and national security be resolved and that decisions be based on substantiated fact. Given that the Navy is a principal stakeholder in the issue, it is probably the most suitable agency to pursue this subject. Also, given that successful resolution is critical to naval operations, the Navy must pursue the R&D necessary to develop sufficient understanding of these issues to enable rational, informed decision making.

E

Mechanical Methods

Mechanical devices have been used to counter mines with varying degrees of success. Such devices include:

- *Bottom trawls*. Based on the British use of bottom trawls drawn from the fishing trade to remove mines lying proud of the bottom, along with moored mine anchors, during World War II, experiments were carried out by the Woods Hole Oceanographic Institution in the 1950s and by the Navy in the early 1980s. As with the British wartime experience, these tests indicated that only slightly modified bottom trawls, whose lower edge penetrates a few inches into relatively soft sand or mud bottoms, were successful in picking up all bottom mines in their path except for those completely buried. Operationally, ensnared mines would be towed periodically from the channel being cleared and deposited in a holding area for later neutralization. The depth of water must be sufficient for the trawler and its operation.
- *Heavy chains*. The previously noted, joint amphibious mine countermeasures (JAMC), including a heavy chain drawn over the ground by two D-7 or D-8 bulldozers to clear surface-resting and partially buried land mines, is intended primarily for use in clearing mines from an assault beach and, perhaps with the addition of a snorkel, out to the surf zone. Bulldozers use plows to clear mines from their own path. However, the plow must cover the full width of the bulldozer, not just the tracks, or the bulldozer itself will become a victim of magnetic and tilt-wand mines passing between the plows. Because of the difficulty of insertion and hookup on a mined beach (particularly one with obstacles), the slow rate of clearance, the vulnerability of the chain to tilt-wand and sensitive mag-

netic mines, and the unlikelihood of effectively clearing tough obstacles, it would seem that JAMC is best suited to the larger cleanup job following the initial assault.

- *Clausen Power Blade (CPB).* The Clausen Power Blade offers a single unique feature: a conveyor belt made from the street track of a dozer, capable of running in either direction and oriented vertically across the front of a D-7. In trials conducted on land, the system has demonstrated its ability to clear an 11-foot swath of land mines buried down to around 10 inches, removing obstacles of up to 4,000 pounds. Mines, obstacles, and the excavated material are stacked in the berm to one side of the vertical conveyor belt mounted above the narrow cutting blade. In these tests, the relatively slow rate of advance, cushioning of the excavated material, and manner in which the smooth surface of the conveyor belt shifts the material to one side reduce the chance that pressure mines will be detonated. To the knowledge of the panel, tests have not been run against magnetic, tilt-wand, and trip wire mines. Neither has the vulnerability of the cutting blade and the conveyor system to a mine blast been tested. The absorption of explosive energy by the mound of dirt before the conveyor may reduce damage to some degree. The conveyor system is a unique addition to the mechanical removal of land, beach, and surf zone mines and obstacles. However, the CPB suffers from difficulty of insertion during the early phases of an assault; its rate of clearance is relatively slow; the berm containing removed mines must be dealt with; and likely delays due to the vulnerability of the blade and conveyor system to mine blast make this, like JAMC, more suited to the larger removal job following the initial assault.

- *Wattenberg Plow (WP).* Designed at LLNL and recommended for consideration by the JASONs during Desert Shield, the Wattenberg Plow is a new approach to the mine plow concept. The strongback with vertical cutting knives at 4-inch spacings, behind a blanket of cross-linked chains, is towed from a distance of 600 feet by a helicopter at speeds up to 20 knots. The knives are torque mounted so that they ride over immovable objects to prevent breaking, and the chain mat is there to keep the system stable and on the ground under tow. A wire basket is mounted on the chain mat to catch mines that are excavated and pass over the strongback. Half-scale tests have indicated that the system can be towed effectively at speeds up to 20 knots, and the system as a whole can perform and survive very well. Static tests with an antitank mine indicated that the system suffered only minor damage that could be repaired quickly and inexpensively in the field. The vulnerability of the helicopter makes it unlikely that the system would be used in the early phases of an amphibious assault or in the breaching of a land minefield subject to cover by artillery. Demonstration of the prototype indicates that although it is useless against obstacles, the plow can be effective in removing mines from inland minefields and from the surf and craft landing zones and would be particularly useful in humanitarian demining. Tests have also demonstrated the helicopter's ability to pick up the WP system and redeploy it for another pass.

- *Guinea pig ships and barges*. Platforms with a signature large enough to activate mines, and "ruggedized" to accept several mine blasts before suffering incapacitating damage, constitutes an old MCM concept. Liberty ships of around 10,000-ton displacement with skeleton crews standing on mattresses to prevent broken bones were used to sweep against U.S. forces' pressure influence mines in the waters around the home islands of Japan following World War II. The Minesweeper Special (MSS) program of the 1960s modified a ship of similar size by using water ballast to reduce shock wave impedance, styrofoam to provide extra buoyancy in case of flooding, deck-mounted long-stem Marion Tregurtha outboard power plants in case of shaft misalignment or propeller damage to the ship's own power system, and a shock-mounted pilot house for the seven-man crew. Tests indicated that the MSS suffered only minor structural damage, and no personnel damage, from a 2,000-pound mine detonated 35 feet off the beam at a depth of 65 feet. A modified tank landing ship (LST) was used as a guinea pig to proof the Haiphong harbor minefields cleared by Operation Endsweep. The guinea pig concept has been tested, it has utility under certain MCM conditions, and it should not be allowed to drop from the corporate memory.

The panel notes the utility of an unmanned, remotely controlled, GPS-navigated barge with sufficient independent compartments, filled with buoyant material such as hardened polymer foam, to withstand several mine blasts of the type expected in the surf zone to high water mark. Once larger mines have been cleared from the deeper water where they will most likely occur, such a barge could provide a channel of its own width to the beach. Precise tracking of the barge as it proceeded would allow accurate definition of a "proven" channel and would allow similarly GPS-equipped assault vehicles to transit safely to the beach. The guinea pig barge could be remotely controlled or have a one- or two-man crew on a shock-mounted platform at the stern. It could also carry enough rigid polyurethane foam material to build a mine-masking road from its bow to the back-beach area, with sufficient bearing strength to be used by vehicles up to the size and weight of tanks. The barge could, of course, be stopped at the first line of obstacles, which may extend as far seaward as the surf zone.

F

An Explanation of the Efficacy of Simultaneous Detonation for Explosive Channel Excavation

Simultaneous detonation of space-buried explosives can produce a buried line-charge analog, in the surf zone and up the beach, forming a channel from which most mines and obstacles are removed in a very short time. Some of the mines may be destroyed, but the purpose of explosive excavation is mine removal—the state of the removed mines is not necessarily relevant. The bottom of the channel is deepened, and mines and obstacles that may not be removed will be on or in the new bottom, which should be deep enough that assault vehicles will not contact them. Contact is important because contact mines are generally the most difficult mines to destroy. After the excavation stage by the line-charge analog, water will flow back into and up the length of the channel. Characteristically, the line-charge analog has a small lip at the end, and much larger lips on the sides. The water flow up the channel will smooth its contour and further reduce the end lip.

It has been suggested that linear sequential detonation might be obtained by dropping, in one pass, a line of spaced penetrating bombs that have fuses with sequential delays. Sympathetic detonation could cause a nearly simultaneous detonation of the line, but this may not be reliable unless arranged for beforehand by special fusing. If a second bomb is in the crater radius formed by the first of the sequence, it will be moved from its original position—this was established before the first crater was formed—and may be damaged by the first bomb's explosion shockwave. If the second bomb is outside the crater of the first bomb, its explosion can throw some of the mines and obstacles back into the first crater.

Random timing of explosions of a line (or any other arrangement) of bombs will also cause mines and obstacles to be thrown back and forth among the craters, and the resulting channel would be partially filled with debris—possibly including still-active mines. The bottom and sides of the channel in these cases would be irregular.

Sequenced explosions also lack the dynamic synergism of simultaneous detonation that creates a channel of relatively uniform width with a small end lip. Water flow, in the sequenced case, will occur after each explosion to smooth crater edges, but the final explosion at the end will not benefit from the previous ones to reduce its lip. It is unlikely that sequential explosions would create as deep a channel as simultaneous detonation of the same amount of explosive material.

A slow sequenced-explosion experiment has, in fact, been done at the Navy's Panama City Laboratory Test Site, in which a first explosion on the bottom (at water depth of about 5 feet) pushed aside mines and obstacles, and after things had settled a second explosion, closer to the edge of the moved mine-obstacles pattern, was set off to push them out some more. It should be possible to continue this pattern to form a cleared channel; this could be continued into shallow water and up the beach, by exploding sequentially so that ejecta are always thrown *away* from the craters previously formed, but, as noted, this is a slow process.

The excavation accomplished by simultaneous detonation results mainly from the explosives' gas bubble; the bubble growth time, of the order of several hundredths of a second, sets the bounds on the degree of simultaneity required. A 1992 study on mine countermeasures conducted by the Naval Studies Board[1] suggested that simultaneity to within ≤ 0.01 seconds is required.

All this assumes that the measure of effectiveness for channel clearance is mine removal. If mine destruction were the measure, simultaneous detonation would offer the advantage only of smoother final channel shape, and a small end lip. Among the impediments to breaching the surf and craft landing zones are the durability of some of the mine types that are typically deployed in near-shore waters and the consequent difficulty of destroying them.

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[1] Naval Studies Board. 1992-1993. *Mine Countermeasures Technology,* Vol. I-IV, National Academy Press, Washington, D.C.

G

Acronyms and Abbreviations

AAAV	Advanced amphibious assault vehicle
ACSAS	Advanced conformal submarine acoustic sensors
ACTD	Advanced Concepts Technology Demonstration
ADS	Advanced deployable system
ALISS	Advanced Lightweight Influence Sweep System
AM	Alternating magnetic
AMCM	Advanced mine countermeasures
AMNSYS	Airborne Mine Neutralization System
ARG	Amphibious ready group
ARSRP	Acoustic Reverberation Special Research Program
ASTAMID	Airborne Standoff Minefield Detection System
ASUW	Antisurface warfare
ASW	Antisubmarine warfare
ATACM	Army tactical missile
ATD	Advanced technology demonstration
ATOC	Acoustic-tomography-climate
C^2	Command and control
C^4I	Command, control, communications, computing, and intelligence
CAPTOR	Encapsulated torpedo
CAVES	Conformal acoustic velocity sensors
CCD	Charged-coupled device
CEC	Cooperative engagement capability
CIA	Central Intelligence Agency
CIMMD	Close-in Man-portable Mine Detector

CLZ	Craft landing zone
CMR/CS	Clandestine Mine Reconnaissance and Countermeasures System
COBRA	Coastal battlefield reconnaissance and analysis
COTS	Commercial off-the-shelf
CPB	Clausen Power Blade
CST	Critical Sea Test (program)
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DSP	Deployable sensor project
EM	Electromagnetic
EOD	Explosive ordnance disposal
ESM	Electronic support measure
FDS	Fixed distributed system
GPS	Global Positioning System
HGI	High Gain Initiative
HOMINE	Homing mine
IR	Infrared
ISR	Intelligence, surveillance, and reconnaissance
JAMC	Joint amphibious mine countermeasures
JASON	Self-nominating academic society that conducts technical studies for the Department of Defense (meets in July, August, September, and October and produces a report in November)
JLAN	Joint littoral awareness network
JMCIS	Joint Maritime Command Information System
JSTARS	Joint Surveillance and Target Attack Radar System
LCAC	Landing craft, air cushioned
LDRT	Low drag ramjet
LF	Low frequency
LFA	Low-frequency active
LIDAR	Light detection and ranging
LLNL	Lawrence Livermore National Laboratory
LLTV	Low-light-level television
LPI	Low probability of intercept
LSD	Landing ship dock
LSM	Littoral sea mine
MAD	Magnetic anomaly detector
M&S	Modeling and simulation
MCM	Mine countermeasures
MCS	Mine countermeasures support (ship)
MEMS	Microelectromechanical systems
MF	Medium frequency
ML(A)	Magic Lantern (Adaptation)
MSI	Minesweeper inshore

MSL	Minesweeping Launch
MSS	Minesweeper Special (program)
NATO	North Atlantic Treaty Organization
NCCOSC	Naval Command, Control, and Ocean Surveillance Center
NMRS	Near-term Mine Reconnaissance System
NRaD	Naval Research and Development (division of NCCOSC)
NSSN	Nuclear-powered attack submarine, new version
NSWC	Naval Surface Warfare Center
ONR	Office of Naval Research
ORSMC	Off-route Smart Mine Clearance
OSD	Office of the Secretary of Defense
PRC	People’s Republic of China
QOL	Quality of life
R&D	Research and development
RAMICS	Rapid Airborne Mine Clearance System
RECO	Remote command and control
RF	Radio frequency
RMOP	Remote Minehunting Operational Prototype
RMS	Remote Minehunting System
ROC	Republic of China
ROV	Remotely operated vehicle
RPF	Rigid polyurethane foam
SAR	Synthetic aperture radar
SEAL	Sea, air, land (team)
SNR	Signal-to-noise ratio
SOSUS	Sound Surveillance System
SPOT	Systeme Probatoire d’Observation de la Terre (French satellite)
SQUID	Superconducting quantum interference device
SSBN	Nuclear-powered ballistic missile submarine
SSGN	Nuclear-powered guided missile submarine
STIL	Streak tube imaging LIDAR
STRAP	Star tracking rocket altitude positioning
SURTASS	Surface Tactical Surveillance System
SWATH	Small waterplane twin hull
SZ	Surf zone
TCP/IP	Transmission Control Protocol/Internet Protocol
UAV	Unmanned aerial vehicle
UEP	Underwater electric potential
USV	Unmanned surface vehicle
UUV	Unmanned underwater vehicle
VDS	Variable depth sonar
VLAD	Vertical line array difar
VLF	Very low frequency

VLSI	Very large scale integration
VSW	Very shallow water
VTOL	Vertical takeoff and landing
VV&A	Verification, validation, and accreditation
WAA	Wide-aperture array
WP	Wattenberg Plow