The Road Ahead

Richard W. Constantine and Richard J. Prengaman

THREAT ADVANCES

The continued proliferation of ballistic and cruise missiles poses a threat to U.S. territory, to our forces abroad, and to our allies and friends. Ballistic missile proliferation has exceeded initial estimates and suggests that these challenges may grow at a faster pace than previously expected. In addition, land-attack variants of cruise missiles may widely proliferate as a cost-effective alternative to high-performance military aircraft. Along with these threats, we find the rapid advance of military technologies for sensing, guidance, and countermeasures. This poses the danger that adversaries will significantly enhance their capabilities by integrating these technologies, some of which are to a great extent available off the shelf, into their weapon systems. Anti-ship cruise missiles (ASCMs) are likely to incorporate penetration aids such as maneuvers, adjunct multispectral seekers, and onboard countermeasures to reduce the effectiveness of shipboard defenses. Similarly, ballistic missiles may incorporate countermeasures and decoys to enhance penetration of defensive systems. When employed with chemical, biological, or radiological weapons, these threats present especially difficult challenges.

Although the United States maintains superiority in most areas of armed conflict, our forces are likely to be challenged by adversaries who possess a wide range of capabilities, including asymmetric approaches to warfare. Asymmetric warfare may encompass mass casualty terrorism and the use of nonmilitary vehicles such as commercial aircraft, boats, or unmanned aerial vehicles to deliver increasingly lethal weapons technologies.

TECHNOLOGY INSERTION

Rapidly advancing military technologies lead to threat advances that must, in turn, be countered with technology advances applied to naval and Joint forces. Furthermore, U.S. military technology advances must be implemented in a manner that allows us to meet emerging challenges rather than to react to force deficiencies. For naval forces the very long life cycles of ship systems compared with threat advances dictate that special attention must be directed to the evolution of legacy systems to sustain military superiority.

The technology development challenge is illustrated in Fig. 1 using DoD 5000 definitions of development and sustainment phases. Historical timelines for radar, missile, and combat direction systems are shown with the optimistic assumption that the pre-system acquisition (i.e., decision to develop) phase would be completed in 3 years. The timelines combine to show that Program Objective Memorandum 2004 (POM 04) new-start decisions would likely result

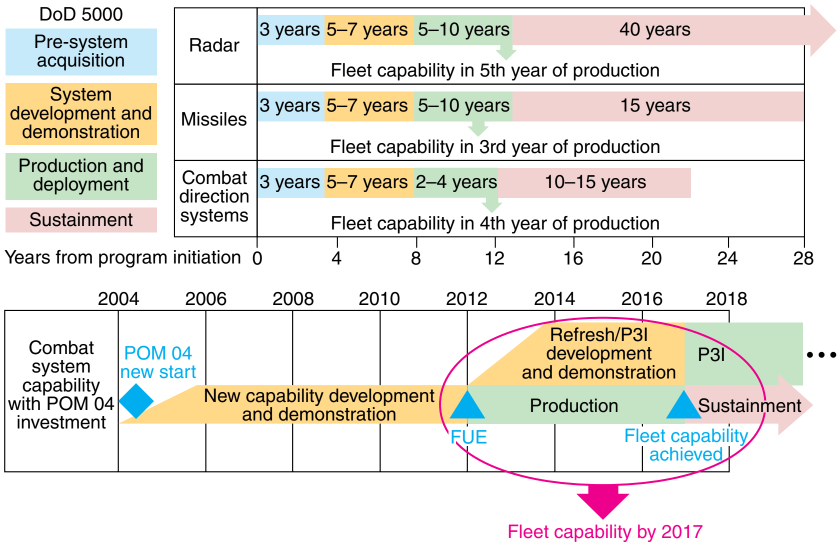

Figure 1. Technology development challenges (FUE = full-up first unit equipped, P3I = preplanned product improvement).

in a significant Fleet capability by 2017. This timeline profoundly influences Navy development decisions and the threat basis and projections that support those decisions. Also significant in Fig. 1 is the historical 40-year sustainment period for major Fleet radars, roughly matching the platform life of combatant ships.

INTEROPERABILITY

Military responses to future threats will require rapid movement and extensive integration of Joint and combined forces. To be successful, operations will demand a flexible, reliable command and control architecture to maneuver, sustain, and protect U.S. forces. Interoperability is fundamental to all future warfare concepts. The critical requirements for interoperability extend development and sustainment timeline issues noted previously (single platform) to the force/combined/Joint level. Here, baseline introduction, certification, commonality, and legacy system accommodation are challenges comparable to the technology development challenge.

COST MANAGEMENT AND ACQUISITION CHALLENGES

The past decade has brought significant pressures on the DoD to do more with less funding. This pressure resulted from increased American peacekeeping efforts after the demise of the Soviet Union and a national resolve to reduce, if not eliminate, government deficit spending. DoD's response has been to involve industry earlier in the acquisition cycle and to outsource many previously inherent government functions. The rationale has been to increase emphasis on cost as an independent variable when developing requirements and solutions to those requirements, and to apply efficient business practices developed by industry during the 1980s and 1990s.

This approach has produced mixed results. Several programs have suffered from optimistic initial cost estimates (to be responsive to "better, faster, cheaper") and unforeseen technical difficulties (a fact of life that seldom is adequately accounted for in initial cost and schedule estimates). This has resulted in programmatic responses that invariably shift production funds to complete development and in turn reduce the number of units purchased and increase per unit cost. An additional consequence of reduced funding has been the trend toward industrial consolidations that can diminish corporate knowledge and capability for a given program.

Another challenge results from the realignment of development authority for ballistic missile defense (BMD) from the services to the new Missile Defense Agency. Specifically, for the U.S. Navy, the combatants that can be configured to provide BMD are multimission by design because they must go in harm's way and defend themselves against a multidimensional threat. Consequently, the addition of BMD can only occur in conjunction with careful integration into the existing multimission combat system. Here, new organizational and management challenges must be addressed in addition to technology development challenges.

POTENTIAL SOLUTIONS

Sensors and Engagement Approaches

Clearly, new sensor and weapon solutions will be needed to meet emerging Navy mission areas. Studies at APL and Navy laboratories have shown that solid-state radar technology will be needed to counter both ballistic and cruise missile threats. The ability to generate very high power aperture with wide bandwidth and low losses is the enabling technology for these mission areas. Although many technology challenges are associated with solid-state radar development, the most serious challenge is the need to minimize the production cost of transmit/receive (T/R) modules that dominate a solid-state radar design (Fig. 2). As solutions to cost are achieved, solid-state radars can be applied to existing self-defense, area defense, and future theater and national defense missions to solve significant technical problems associated with environmental clutter and enemy countermeasures.

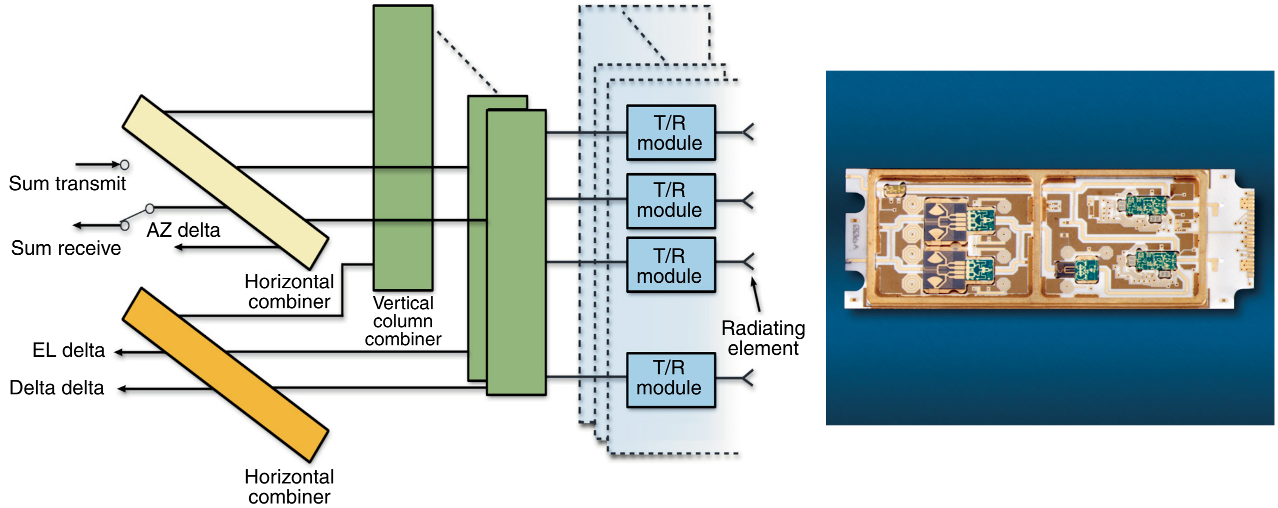

Figure 2. Solid-state radar (left) performance advantage and cost are closely related to the transmit/receive (right) building blocks. Module shown is 2.92 × 8.38 cm.

It is generally recognized that new construction ships must include solid-state radar technology despite the cost risk. This is consistent with the reality of ship system development and sustainment timelines relative to the threat evolution described earlier. Fortunately, the transition to solid-state radars is aided by the inherent scalability of radar capability to mission requirements by the number of T/R modules used and by the evolution of module performance (i.e., planned performance growth). As technology evolves, all major mission areas would be implemented using common components to provide solid-state ship configurations such as the one illustrated in Fig. 3.

Although solid-state radar is an enabling technology path for shipboard sensing, active missile seeker technology is expected to fulfill an enabling role in future air defense. This technology is essential to the naval combatant's ability to engage enemy forces beyond the ship's horizon. At least four key capabilities will be enabled by active seeker technology:

- ASCM beyond-the-horizon defense
- Land-Attack Cruise Missile (LACM) overland defense
- Aircraft overwater/overland engagement beyond the horizon
- Defeat of ASCM, LACM, and aircraft threats with onboard countermeasures

The ability to engage ASCMs beyond the horizon can be expected to significantly enhance force protection at sea and allow much more flexible deployment and movement of ships in contested environments. As shown in Fig. 4, this technology will have a transformational impact on Fleet area and self-defense, with emphasis on defeating threats to our forces at sea beyond the horizon, before they have a chance to penetrate ship defenses.

In this "pre-penetration" region, ASCMs are typically very vulnerable to attack by the ship's missile

Figure 3. Conceptual "solid-state ship" with air defense and tactical ballistic missile defense missions.

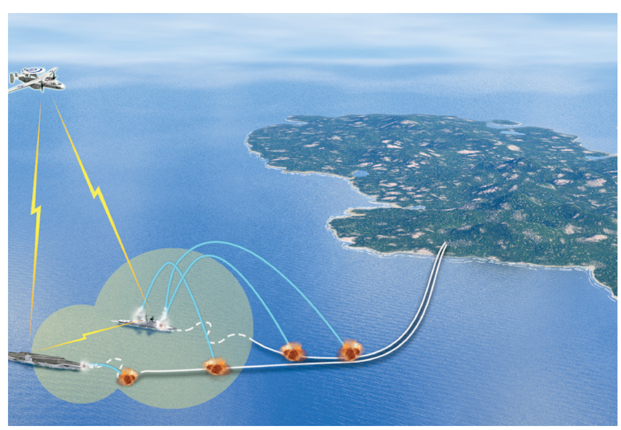

Figure 4. Engagement of ASCMs beyond the threat's "penetration" region negates many of the key features of this class of threats.

engagements. On the other hand, if engagements take place within the horizon, the ASCM can be expected to use penetration aids such as maneuvers, step-downs, turns, and multispectral seeker techniques to reduce the effectiveness of ship defenses. By defeating the threats at or beyond the horizon, the key advantages of ASCMs are negated. Of course, extended ship defense must continue to be complemented by high-quality self-defense, with the expectation that few threats will reach the self-defense region and none will reach our ships.

In addition to area defense over water, active seeker technology will extend air defense to overland threats including hostile aircraft and LACMs (Fig. 5). This capability is especially important in operations where critical forces ashore must be protected from airborne threats. The technology is clearly enabling for the overland air defense mission. The large speed advantage of an Extended Range Standard Missile compared to fighter aircraft strongly supports Standard Missile engagement of overland threats as an attractive alternative.

Active seeker technology can also be expected to provide a viable solution to onboard countermeasures in threat aircraft and cruise missiles. Here, the active seeker radar in the defensive missile can be implemented at frequencies and bandwidths not feasible in semi-active illumination systems, providing both resolution and signature advantages to defeat threat countermeasures. This technology is expected to be implemented first in an extended-range active missile with potential for sharing the technology for an Evolved SeaSparrow Missile upgrade.

Active seeker technology, especially in conjunction with side thruster technology, can also be used for sea-based terminal Tactical Ballistic Missile Defense (TBMD). The PAC-3 ground-based TBMD system already employs those two technologies to provide hit-to-kill (HTK) lethality against ballistic missiles. Millimeter-wave active seeker technology provides the required steering accuracy, and the side thrusters provide the required responsiveness and agility to ensure HTK.

As part of the original sea-based TBMD effort, the Standard Missile Program had been planning to introduce side thrusters in the next generation of Navy Area TBMD missiles and had begun prototyping a unit that would replace the current Mk 133 blast fragmentation warhead section. Side thrusters will also improve accuracy against cruise missile targets. However, because of countermeasures, HTK against cruise missiles is more difficult to achieve and therefore some form of warhead will still be required. PAC-3 employs a small lethality enhancer for that purpose. Because the Standard Missile airframe is substantially larger than the PAC-3, and because a side thruster will require only approximately half the space used by the current warhead section, a substantial warhead could still be accommodated in Standard Missile if side thrusters were employed for cruise missile defense.

Networking and Open Architecture

The previous section described technology insertion in radar and missile engagement elements. These are key elements in the Navy's sweeping transformation from a platform-centered to a network-centered force. As defined in Ref. 1,

> The primary tenant of network-centric warfare is the use of mutually shared information and a common operational picture to enable the coherent employment of naval forces as a single, distributed entity; one that derives its power from the networking of geographically dispersed elements, sensors, decision makers, and shooters. Essentially this transformation seeks to harness the explosion of information technology to give commanders at all levels timely access to more relevant information, to improve their overall situational

Figure 5. Overland defense of forces ashore (left) against LACMs (top right) and hostile aircraft (lower right) via Extended Range Standard Missile with active seeker technology.

awareness, and to facilitate their ability to plan, coordinate and execute effects-based combat operations.

Clearly, the enabling technology to initiate this transformation at the air and missile defense level has been the Cooperative Engagement Capability (CEC). Conventional data link systems have attempted to share sensor track data without a disciplined investment in accommodation of each sensor's data rate, latency, and track filter bandwidth. Warfighting experiences have shown that the more participants that share track data in this way, the less accurate, less reliable, and more confusing the information is. CEC solved this fundamental problem, first by bringing the low-latency network data directly to the sensor and second by requiring that association and data distribution be at the measurement level rather than the track level. This allows for the first time the critical "situational awareness" function to meet requirements for coverage, continuity, accuracy, swaps, and duals for all participants in the network.

CEC by itself, however, is not the total solution to the single integrated air picture (SIAP). Tactical data information links (TADILs), like Link-11 and Link-16, are used throughout the services and by our allies, and will continue to play a very important role for SIAP. The CEC Operational Evaluation (OPEVAL) demonstrated numerous interoperability problems among all these TADILs and the combat systems they support, which must be corrected before a true SIAP can be achieved. Critical experiments, like the SPAWAR Multi-TADIL Processor, may demonstrate practical, affordable, near-term approaches for addressing these issues. In addition, emerging concepts such as FORCEnet may be central to commanding Joint operations from the sea.

The network-based transformation taking place in the Navy is a goal throughout the DoD. Future military responses will require the rapid movement and integration of Joint and combined forces. This concept, with Navy emphasis, is illustrated in Fig. 6 with Air Force,

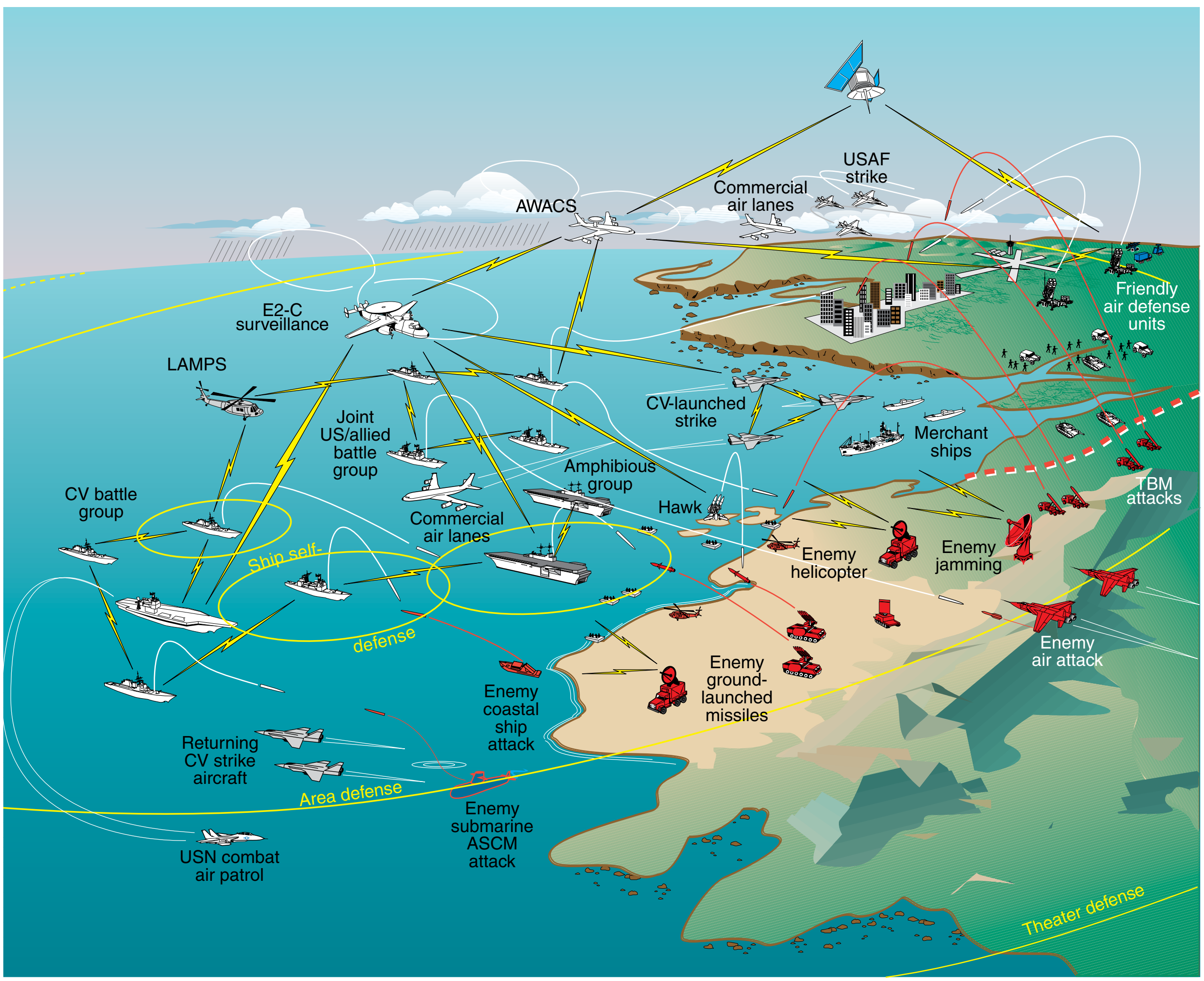

Figure 6. Future littoral military operations will require coordination and integration of Joint and combined forces using network-centric warfare technology.

Army, Navy, and Marine force operations in a littoral environment. Here, end-to-end (detect through engage) interoperable networks are required for secure planning and operations, including shared situational awareness and integration of Joint fires, maneuver, and intelligence.

To meet the Navy's transformation goal, the CEC network must be effective as a "backfit" with sensors and combat system configurations that were designed prior to network-centric warfare concepts. For example, procurement planning through FY2008 will fund 53 CEC installations on Aegis destroyer and cruiser combatants, many of which will also receive upgrades to the AN/SPY-1 radar. Similarly, in the same time period, 29 E-2C aircraft will be funded for CEC installation, with many of these also receiving the airborne radar upgrade to the phased array configuration as part of the Radar Modernization Program.

These ships and aircraft must provide the "road ahead" for over-the-horizon extended area anti-air warfare (AAW) and overland engagement of hostile aircraft and LACM, in conjunction with the active seeker variant of Standard Missiles. The ships must also provide advanced capabilities for cooperative sea-based BMD. A major challenge will be the evolution of both airborne and shipboard combat system architectures. It is expected that open system architecture techniques such as those implemented in the Ship Self-Defense System (SSDS) will provide the road ahead for cost-effective combat systems.

The upgrade plans described above represent a major step toward the Navy's transformation goals. From this beginning, network-centric warfare is expected to continue to accelerate in capability and importance for decades to come. Extending the composite network to Joint and combined forces must remain a priority for each service and for the DoD. Such a network will ensure shared battlespace awareness and will enable the development of Joint command and control capabilities for both distributed and headquarters systems with adaptive mission planning tools such as those pioneered in the Area Air Defense Commander (AADC) system. This will allow U.S. forces to operate within an adversary's decision cycle and respond to changing battlespace conditions.

Networked integration of airborne and space-based systems can be expected to play an increasingly important role in Navy counter-air, strike, and BMD mission areas. These will include multifunction unmanned aerial vehicles, enhanced space-based radar, and national satellite systems as well as commercial imagery and manned aircraft. They will also be combined with Navy networked surface and slow air data from shipboard radars to provide a robust, continuous target base for defense against asymmetric threats.

Disciplined Development Process

Reference 2 describes APL's systems engineering approach to air and missile defense, a process that has been developed by the Laboratory over several decades of Navy AAW weapon system development. Figure 7 illustrates the basic steps in this approach, which are being applied to the Sea-Based Midcourse TBMD Program (formerly called the Navy Theater Wide TBMD Program).

The process begins with a recognition and quantification of a need, which may result from a threat advance, the emergence of an entirely new threat, or the availability of new technology that promises improved performance at lower cost. The quantification of that need is especially important to focus potential solutions. Several solutions are initially developed to respond to the need and to identify the areas of technical risk that must be reduced to ensure feasibility. Risk reduction experiments are performed to determine which potential solutions are most attractive and to iterate the requirements to satisfy the needs at the most reasonable cost and lowest risk. This risk reduction step is especially important and has played a major role in the definition of Aegis (e.g., the SPY-1 Advanced Multi-Functional Radar Prototype), all versions of Standard Missile (e.g., the infrared seeker and dome for Standard Missile-2 Blk IVA and the kinetic

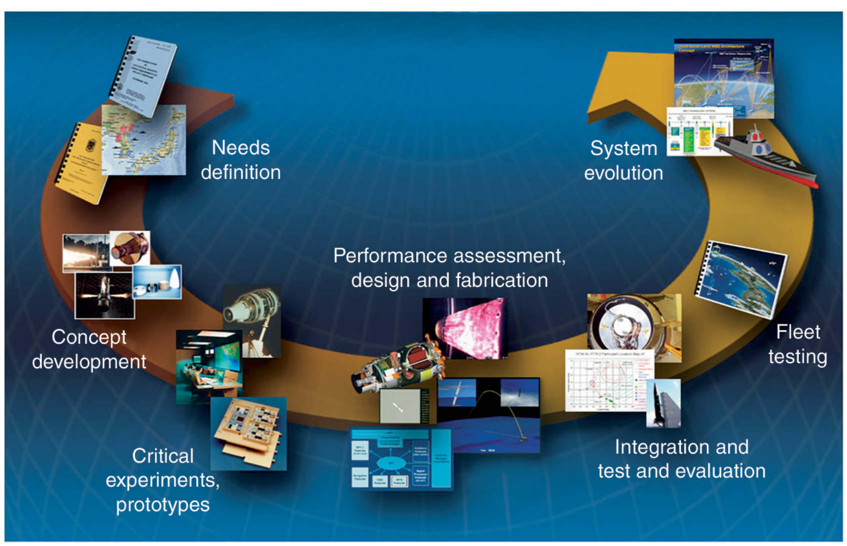

Figure 7. A system development cycle for Sea-Based Midcourse TBMD. The cycle shows systems engineering progression from top-level requirements and concept formulation to Fleet introduction and system evolution.

warhead for Standard Missile-3), SSDS (e.g., the networked sensors and communications infrastructure), and CEC (e.g., the Data Distribution System). The Missile Defense Agency has refocused its efforts to emphasize this step for each element of the BMD system.

Once the first three steps have been successfully concluded, development proceeds to engineering and manufacturing development (EMD). This phase focuses on developing a producible design of the desired solution, including the operational and logistical functions that are required to use the weapon. Again, as the development proceeds, refinement of the requirements occurs to ensure producibility, performance, reliability, and cost containment.

A critical aspect of EMD and the prototyping phases is quality control. So many development projects have stumbled here, resulting in substantial program prolongation (e.g., Theater High Altitude Air Defense) and even cancellation. These phases in particular require unfailing discipline—from piece parts inspection through all-up environmental testing. Proven, highly successful processes have been developed in the Navy, especially for missile development, that ensure such discipline.

The test and evaluation phase also requires great discipline to ensure that assessments of very expensive and complex test articles yield the necessary data. Test and evaluation is a bottom-up process, from the smallest parts to systems of systems. Field-testing in particular (such as that conducted with the AADC prototype), using operators who will actually employ the weapon system, is critical to understanding the system's military utility in the environment in which it will be put into service. This phase may again impact final performance requirements prior to operational use.

Once the weapon system passes operational evaluation and approval for full-rate production, the process begins again with the definition of future evolutionary needs and solutions. This overall process has been well characterized over many decades. Shortcuts have never proven effective; in fact, they have been detrimental. Our challenge for the future is to insist on using proven techniques under pressure to shorten development cycles and reduce costs. This does not mean that improvements to the previously described development process should not be pursued. To the contrary, the current process has resulted from continued refinement over time. However, the key ingredient is a disciplined systems engineering process.

APL CONTRIBUTIONS

From the development of the proximity fuze in 1942 to the successful OPEVAL of CEC in 2001, the Laboratory has been at the forefront of air and missile defense development. There are no ship-based air or missile defense systems in the Navy that the Laboratory has not contributed to or conceived. Along the way, through a continuous investment by the Navy, DoD, and APL, the Laboratory has developed a unique assemblage of staff, tools, and facilities, as well as a problem-solving culture, all devoted to recognizing and solving air and missile defense problems. Examples of new facilities and tools just being completed include high-frequency anechoic chambers for testing future active radio-frequency guidance systems, vacuum chambers for testing the infrared sensors of exo-atmospheric kill vehicles, composite tracking network-generic processors, open architecture combat system test beds, and end-to-end high-fidelity simulations for conventional AAW, BMD, and LACM defense.

The Laboratory's expertise in support of air and missile defense spans spacecraft design and development, radar and electro-optical sensors, computer systems, communications systems, displays, networking, and all facets of missile design and development. We use this expertise in conjunction with government-led teams to identify needs, translate those needs into quantifiable requirements, develop responsive concepts, identify and conduct critical proof-of-concept experiments, evolve the technical approaches with industry, assist and often lead test and evaluation (both on land and at sea), and serve as a corporate memory as the new system evolves.

The Laboratory team is especially well grounded in the fundamentals of disciplined systems engineering, which is so vital to the successful development of complex and advanced systems. As a by-product of that expertise, the Laboratory offers graduate-level courses in many technical disciplines, including systems engineering and technical management, that have helped shape emerging government and industry leaders in air and missile defense. This culture, our demonstrated performance, and the educational opportunities available have helped to develop a trusted agent relationship with our government sponsors and industry that has contributed to our effectiveness.

As we move into the 21st century, the APL approach that has proven so effective in the past—namely, disciplined systems engineering, extraordinary technical breadth and depth, the right tools and facilities, a problem-solving culture, and a solid relationship with our sponsors and industry—will serve the nation well in meeting future air and missile defense challenges.

REFERENCES

[1]Balisle, P., and Bush, T., "CEC Provides Theater Air Dominance," in *Proc. U.S. Naval Inst.* (May 2002).

[2]Krill, J., "System Engineering of Air and Missile Defense," *Johns Hopkins APL Tech. Dig.* **22**(3), 220–232 (2002).

THE AUTHORS

RICHARD W. CONSTANTINE is a member of the Principal Professional Staff and the Laboratory Executive Council. He received a B.S. in aeronautical engineering from Princeton University in 1964, an M.S. in mechanical engineering from Purdue University in 1966, and an M.B.A. from the University of Maryland in 1976. He joined APL in 1966 in the Bumble Bee Propulsion Group of the Aeronautics Department where he specialized in ramjet engine design, missile composite design, digital flight simulation, and test and evaluation. Mr. Constantine moved to the Fleet Systems Department to become Standard Missile Program Manager in 1983 and was appointed Program Area Manager for Surface Combat Systems in 1989. In 1996, he was named Head of the newly formed Air Defense Systems Department. He has participated in numerous Navy, OSD, and congressionally appointed studies focused on missile defense. His e-mail address is rick.constantine@jhuapl.edu.

RICHARD J. PRENGAMAN received his B.S. degree in electrical engineering from Carnegie Mellon University in 1965 and his M.S. degree in numerical science from The Johns Hopkins University in 1972. He joined APL in 1969 and has been a member of the Principal Professional Staff since 1981. He is currently the Chief Combat Systems Engineer of the Air Defense Systems Department. Mr. Prengaman has an extensive background in Navy radar and missile integration systems and has been the technical director of several large programs in which APL served a design agent role for the Navy in “first-of-a-kind” systems development. These included the AN/SYS-1 and AN/SYS-2 automatic detection and tracking systems in the late 1970s and early 1980s as well as the Ship Self-Defense System (Mk 1 and Mk 2) from 1992 to 2000. From 1986 through 1990 he led a six-country international team of sensor experts in the definition of advanced combat systems for NATO Shipboard Air Defense. His e-mail address is richard.prengaman.sr@jhuapl.edu.