2010

Broadening the Trade Space in Designing for Warship Survivability

Harney, Robert C.

Naval Engineers Journal
http://hdl.handle.net/10945/43501

Broadening the Trade Space in Designing for Warship Survivability

Robert C. Harney

Abstract

In littoral warfare against a competent adversary, affordable levels of stealth and defensive weapons will not prevent our warships from being hit by antiship weapons. As our ships will be hit, we must design them to absorb these hits and continue to fight. In this paper, we consider the future threat and four approaches to design for survivability: stealth, defensive weapons, passive defensive design, and increased numbers. The advantages and disadvantages of each approach are discussed. Only a balanced strategy that incorporates the elements of all four approaches is likely to be both survivable and affordable.

Introduction

For the last few decades, we have been designing and building warships based on a design philosophy that evolved during the era of the Maritime Strategy (Palmer 1996; Watkins 1986; Brooks 1986). Under this strategy, the major threats to warships would come from submarine-launched cruise missiles or torpedoes, cruise missile attacks from massed elements of the Soviet Fleet, and/or cruise missile attacks by division-sized bomber elements of Soviet Naval Aviation. Any and all engagements involving our Navy would be blue water actions (in open oceans off of the continental shelves). The maximum credible attack consisted of perhaps a dozen torpedoes targeted against a limited number of ships (usually the aircraft carrier and its immediate escort) or roughly 100–200 cruise missiles targeted against a carrier battle group.

Defense against the submarine threat consisted of semi-independent patrol by one or two nuclear attack submarines, screening by several destroyers (carrying hull-mounted, towed, and helicopter-borne sonar systems and antisubmarine torpedo weapons), and self-defense antitorpedo decoys (e.g., Nixie). Defense against the cruise missile threat involved multiple layers. Carrier-based aviation would engage the surface fleet or bomber forces before those forces could launch their missiles. Shooting the "archer" was preferable to shooting down the "arrows." Invariably, a sizeable number of "archers" would survive the air attack or be able to fire their "arrows" before being shot down. A few dozen missiles would remain for the next layers of defense. Any remaining available carrier aircraft would attempt to shoot down in flight any missiles they could. Standard missiles (SM-2) would engage the cruise missiles as soon as the AEGIS system (or its Cooperative Engagement Capability upgrade) could detect and track them. At shorter ranges, Sea Sparrow or Rolling Airframe Missiles (RAM) would engage those cruise missiles surviving the SM-2 layer. At minimum range, the Phalanx Close-In Weapon System (CIWS) would lay down a barrage of bullets at any target surviving the Sea Sparrow or RAM attacks. All of the preceding layers would be backstopped by SLQ-32 electronic warfare

DOI: 10.1111/j.1559-3584.2010.00248.x

systems and a variety of chaff and infrared decoys. Furthermore, given the relatively inaccurate targeting available to the enemy and the modest performance of then-available missile seekers, significant improvements in survivability could be achieved by incorporation of as much stealth (primarily radar cross-section reduction) as practical into later warship designs. This reduced the probability that a threat missile could find and hit its target, even if it were not successfully engaged by defensive weaponry.

Given the Cold War threats, analysis consistently showed that only a few, if any, missiles or torpedoes would survive to impact our warships. Thus, it proved cost-effective to design our Maritime Strategy combatants (basically the FF-7, DD-963, DDG-51, CG-47, and CVN-68 classes) to survive only one or two hits.

The dissolution of the Soviet Union ended the utility of the Maritime Strategy, but did not eliminate the existence of threats. New threats are emerging and these are driving the United States Navy to develop new strategies. At the present time, it seems certain that any overarching strategy will involve at least some conflict in littoral waters (Office of the Chairman JCS 1996; Office of the Chairman JCS 1997). The implication of naval conflict in littoral waters is that naval combatants will come into the range of far more numerous threats. Coastal patrol craft, land-launched cruise missiles, ballistic missiles, coastal patrol submarines (SSK), moored and shallow-water bottom mines, short-range land-based aviation, and even land-based artillery (long-range "superguns" (Gilreath et al. 1999; Lowther 1991) must be contended with in addition to the classical maritime strategy threats. Furthermore, attacks may occur at reduced ranges and may involve weapons with both improved targeting and more robust guidance systems. Recent studies of the enemy area denial problem (Mahnken 1998) have indicated that negation of United States force projection capabilities by a hostile state requires an ability to keep the United States Navy out of that state's littoral waters. One of the unanimous conclusions of these same studies was that the hostile state could and should invest in large numbers (many thousands) of antiship missiles, as well as mines and submarines.

If a limited naval force (such as one or two carrier battle groups or less) enters the littoral waters of an adversary, it can expect massive missile attacks in numbers 3–10 times larger than the maximum credible blue water threat. In littoral waters, more of the threats will be land-based or sea-based (small patrol craft) rather than airborne. This makes it harder for long-range aviation to target the archers before launch, even if the evolving rules of engagement permit such engagements. Shorter launch ranges on the part of threat aircraft may prevent aviation from destroying any missiles in flight. Thus, a higher fraction of the much larger attack will likely survive to confront the inner layers of the defense. If we use an analysis similar to that performed for the blue water threat (this analysis is detailed in a later section), then each ship in a littoral engagement can expect at least 8–10 hits and possibly more than 15 hits. With current ships, this would almost certainly mean complete loss of combat function, if not sinking. This suggests that our current naval force is not survivable in high-intensity littoral conflicts. However, future combatant designs must be survivable in these environments if the United States is to remain a dominant world power.

There are four competing strategies for survival against massive attacks: design the ship to be invisible to the threat (stealth), provide the ship with sufficient defensive weapons to counter the threat (active defense), design the ship to absorb without unacceptable damage the punishment the enemy can inflict (passive defense), or design much smaller ships that can be built and deployed in such large quantities that enough will survive any attack (increased numbers of minicombatants that are "expendable" in the same way that individual infantry soldiers are expendable). Survivability is generally considered to have two components: susceptibility (the ability of the enemy to detect, localize, engage, and hit a target) and vulnerability (the degree to which a hit can cause serious damage to the target). An arguable third component—recoverability—can be incorporated into vulnerability without loss of fidelity in the following arguments. Stealth, active defense, and increased numbers all address the susceptibility aspects of survivability. Passive defense addresses the vulnerability aspects. In this article, we will examine the ramifications of the following four approaches, given the postulated future threat.

The Future Threat

In the following sections, we will examine the impacts on warship design, given four different approaches to handling a postulated threat. We assume a threat that is not the standard threat being used by current requirements setters. When the Soviet Union collapsed, requirements setters looked far and wide for new threats against which to pit their new system developments. Unfortunately, they concentrated on the near term and not the long term. In general, the assumed naval threats tended to mirror or at best slightly evolve from the existing capabilities of known adversaries. The threats are basically minor navies equipped with limited numbers of first-line ex-Soviet combatants (possibly including a number of submarines) equipped with substantial but limited numbers of antiship cruise missiles. It was expected that current ship designs were sufficient to stand up to these short-term threats. Little emphasis was placed on the forces of countries considered as unlikely adversaries or on the reactions that adversaries might take to counter (in the long term) our known actions, i.e., our existing and planned forces and equipment.

At the request of the Office of Naval Research and the Executive Panel of the Chief of Naval Operations, the Naval Postgraduate School undertook to develop a credible and fully justifiable set of long-term (ca. 2020) threats (Melich et al. 2000). Several teams of students were assembled, each team representing a different potential 2020 adversary to the United States. Each team had four to five officer students (drawn from each of the four military services and more or less equally split between national security and engineering studies) and one or two faculty advisors (typically highly experienced in the systems engineering, design, development, and manufacture of large-scale defense systems). Over the course of several months, each team proceeded to develop their military force structures in three successive 7-year epochs. In each epoch, the team was given an estimate of the military budget it would have available and a national military strategy. The budget and strategy were developed by outside teams of expert consultants drawn from industry, academia, and government. Wherever possible, the consultant teams included nationally recognized economic, political, and intelligence experts on the countries being gamed. The consultant groups were chartered to develop strategies and budgets that represented the groups' best estimates as to the actual future course of events. The only guidance given to the groups was to assume less than benign intentions on the part of the foreign government and that the United States would probably oppose any military expansion of influence beyond the borders of that state. Obviously, if a potential adversary decides on peace, then there is no need for a military response on the part of the United States. As we were looking to define possible future adversary characteristics, we forced each of the targeted nations to be adversarial. However, no guidance was given as to the nature that the adversarial character should assume.

Given its country's strategy and budget, the student team was free to develop forces and equipment consistent with that strategy and that budget. Resources were allocated among research & development (R&D), manpower, procurement, operations, intelligence acquisition, and counterintelligence. All aspects of the military (land, sea, air, and space) were considered in the allocations. Specific R&D programs and specific equipment acquisitions were identified. Equipment acquisitions could only be made from those items that had been allocated full

R&D funds in prior epochs, or that were available on the international arms market. The systems engineering faculty validated budget estimates as to R&D cost, and unit equipment costs for every hardware type based on their extensive experience (typically 20 or more years each in the defense industry). The input to the first epoch was the best available intelligence on current budgets, force structures, and defense R&D investments. The outputs of the first epoch were used by the consultant groups to define the inputs to the second epoch and the outputs of the second epoch were used to define the inputs to the third epoch. In this manner, our knowledge of that country in 1999 was projected in a budget- and politics-constrained fashion out to the 2020 time frame.

This approach does not generate a probable future, but does define a plausible and realistic one. The results of this analysis are politically sensitive, identifying enlightened forecasts of what potential adversaries might do. To avoid condemning nations for actions they have not yet taken (and hopefully will never take), we will not identify the specific countries or their specific responses. However, some responses occurred for every country studied. This indicates that a potential future threat will likely have at least these elements in its future force structure. We will describe only the maritime-relevant responses.

In reading the threat description below, remember that the countries involved planned for potential conflict with the United States at a time roughly 20 years in the future. They reshaped their militaries based on long-term strategies that in turn considered the directions the US military was taking. Being composed of capable military officers, the country teams rightly assumed that the best strategy was to concentrate on defeating United States weaknesses, not to mirror United States capabilities. They had two decades and 20 years of defense budgets in which to accomplish their goals. The threat description is not based on what they were doing in 1999, but on what they could do if they perceived that conflict with the United States was inevitable.

Specifically, there was increased emphasis on having a credible diesel submarine force. The richest adversary nations (near peer competitors) developed their own submarines in substantial numbers; poorer adversary nations (regional competitors) purchased relatively modern Soviet or European submarines in modest numbers. The submarines carried extremely capable, long-range torpedoes, a substantial fraction of which had wake-homing seekers.

Each country invested a sizeable (but balanced) share of its defense budget in antiship missiles. Even the poorest country studied bought thousands of Exocet or Silkworm missiles and reasonably mobile launching platforms without straining its defense budget to the breaking point or ignoring the formation of a well-rounded military. The near peer competitor nation purchased or developed tens of thousands of modern missiles. The antiship missiles could be launched from at least five different kinds of platforms: long-range attack aircraft, littoral patrol craft, blue water surface combatants (corvette or larger), submarines, and mobile land-based launchers. Launchers were purchased in sufficient quantity to allow multiple massive attacks (1,000 missiles per attack in flight at one time) to be delivered nearly simultaneously at several different points anywhere in the adversary's region of operations. Seekers on the missiles included a mix of relatively unsophisticated radar seekers (as available today) and very sophisticated advanced radar, imaging infrared, and multimode seekers (to be developed in the next 10–15 years).

Tens of thousands of missiles seem large, but it should be remembered that highly capable antiship missiles (e.g., Harpoon) cost roughly US$500,000 each, while less capable but serious threats might cost as little as US$100,000 each. Thus, 10,000 missiles cost only US$5 billion dollars or less, the price of a single aircraft carrier, and only 1% of the 2009 US defense budget.

Furthermore, those 10,000 missiles would probably be acquired over 20 years, making the annual expenditure <US$250 million, a small fraction of the defense budget of any nation that could be considered a regional competitor. It should also be noted that the United States does not expect to face major naval threats in its littoral waters, and so it has not acquired weapons or shaped its forces to defeat such a threat, as our adversaries are likely to do. Nevertheless, the United States has roughly 6,000 Harpoon antiship missiles, roughly 20,000 antiradiation missiles (ARM), and 37,000 Maverick missiles that could be targeted against ships, and huge quantities of general-purpose aircraft bombs that can be used against any target (Federation of American Scientists 2009). Neither the ARM nor the Maverick missiles are intended for antiship use, and because of their smaller warheads, are unlikely to sink a major combatant, but can cause severe damage either to a ship or its combat systems. A few hits might be sufficient to render a warship incapable of fighting or defending itself. As a consequence, any ship must defend against ARMs and anti-armor missiles just as if they were large ship-killer missiles.

Each country invested heavily in naval mines. These tended to be evenly divided between deepwater CAPTOR-like mines, moored mines, shallow-water bottom mines, and surf-zone mines. Most mines were expected to possess enough intelligence to permit targeting of specific ship classes, to make sweeping difficult, and to permit mines to be remotely activated and/or deactivated.

An additional output of this study was a detailed vulnerability analysis of US forces with respect to area denial. This unpublished analysis matched almost one for one an independent analysis conducted by the Defense Science Board (1995). Missiles, mines, and submarines in large numbers were near the top of each list of threats to our naval forces. These three threat developments alone (there were others of lesser importance), when fielded in large numbers, will have major impacts on combatant ship survivability. Let us first examine the impact on ships built using the stealth approach to survivability.

Design for Stealth

If a combatant ship cannot be detected by a missile or a torpedo seeker, it cannot be hit except by luck. Stealth functions to reduce the detectability of a ship to levels that are assumed to be acceptably low. For example, an active radar missile seeker has the highest probability of acquiring a target ship if it is capable of detecting that ship as it rises above the seeker's radar horizon. For sea-skimming missiles, this corresponds to a range of 20–30 km (depending on the height of the ship). Assume that the missile was not aimed precisely at the target at launch and that the seeker can barely detect the target at this range (in practice, real seekers can have longer detection ranges against traditional targets). By reducing the detection range by an order of magnitude, the probability of acquisition of the ship target could be reduced to 10% of its original value by a direct reduction in the ocean area that could be searched. Such a reduction in the detection range can be achieved by a four order of magnitude reduction in cross-section. This is the primary mechanism by which stealth reduces the susceptibility of a target.

There are three basic problems with design for stealth. First, stealth is expensive. Every aspect of exterior design must be meticulously controlled and special materials must be used. Second, stealth is difficult to maintain. Modifications to a ship's exterior, corrosion or aging of external materials, sloppy maintenance, failure to properly close all external doors/hatches/panels after opening for operations or maintenance, failure to stow supplies, equipment, and tools, and opening of doors and hatches for normal operations can significantly increase the detectability of a ship. Third, stealth is a moving target. Acceptably low signature levels at one time may not (and probably will not) remain acceptably low in the future. Advances in component technology, packaging, or signal processing permit significant advances in detection capability for seekers of the same basic type. Furthermore, stealth in one signature does not imply stealth in other signatures. A ship designed for a low radar cross-section may be undetectable to a conventional scanning radar seeker. However, if the seeker technology changes to use synthetic aperture radar, the low cross-section against one kind of radar may not prevent detection at useful ranges by another. Similarly, if a ship designer designs for a low radar cross-section, his design may be detectable by passive infrared seekers. If he also controls the infrared signature, the ship may be detectable by laser radar seekers, and so on. Improvements in targeting can also negate the benefits derived from stealth. Reducing the detection range by an order of magnitude has no effect on detection probability if the missile is directed to the target so accurately that the missile always finds the target within its reduced detection range.

It is not difficult to redesign a conventional target to achieve a significant reduction in signature. It is very difficult to reduce the signature to truly undetectable levels. Even the B-2 stealth bomber is not undetectable: an ABM-quality phased-array radar operating at megawatt average power levels would be capable of detecting the B-2 at ranges capable of allowing intercepts. However, in most cases, it would not be cost-effective to deploy such radars against the limited B-2 threat. Furthermore, making the B-2 invisible to conventional air defense radars increased the cost to such high levels that we could not afford to buy more than a handful. At last count, we had procured a total of 21 aircraft at an average cost of US$2.1 billion each (Government Accounting Office 1997). The same fate is befalling the F-22.

To design ships that will be undetectable by advanced seekers of the 2020 era (or worse the 2050 era, when ships designed today will still be required to operate) will almost certainly be prohibitively costly. Unless we can afford to build several new surface combatants each year, we will suffer a continual decline in the size of the Navy, and our ability to conduct the kinds of operations we currently conduct will be hampered by sheer lack of ships. Given the current surface combatant ship construction budget allocations, several ships per year can only be achieved if the individual ship cost is much <1 billion dollars. By comparison with the B-2 costs, it seems exceedingly doubtful that these subbillion dollar ships can be designed to be truly invisible to even one class of seekers, let alone several. The more signature elements that must be controlled, the more expensive will be the resulting design. This does not mean that all signature reduction is not worthwhile. The first few order of magnitude reductions will be relatively inexpensive and may eliminate the threat from thousands of existing low-technology seekers (such as simple active radar seekers or reticle-based infrared seekers). However, it is not sensible to base survivability in the 2020+ era solely on stealth.

It should be noted that one possible component of the littoral threat arises from hundreds if not thousands of small boats possibly carrying antiship missiles, but more likely carrying direct fire (unguided) anti-armor weapons or massed explosives. Many of these boats may be camouflaged (or in fact do double duty) as fishing boats or coastal commerce craft. Pure chance will bring one or more of these craft into near-collision proximity with the combatants on a regular basis. Shadowing or direction by long-range surveillance assets will make such contact a virtual certainty. No amount of radar signature reduction, infrared signature reduction, acoustic signature reduction, or even visual signature reduction will protect a ship from recoilless rifle fire or shoulder-launched antitank missiles fired at point-blank range.

If the threat consists of large numbers of quiet submarines or mines, the design for stealth will similarly not provide the degree of survivability desired. It is not hard to see that any submarine equipped to detect other stealthy submarines and operating at low speeds to minimize its own noise will easily be able to detect surface ships regardless of the amount of acoustic stealth achieved. Mine threats will also not be eliminated by stealth. Given that the threat is likely to use multiple-influence as well as contact fuzing, mine clearance (detection, localization, and neutralization) is the only defense that is likely to succeed.

Design for Active Defense

The second approach to survivability is to defeat an engagement after it has been initiated. That is, to incorporate active defenses to intercept and destroy or degrade the ability of the threats to hit the intended target. Historically, surface ships have relied on layered defenses involving aircraft, long-range missiles, short-range missiles, guns, electronic jammers, and decoys. However, a ship or a battle group can carry only a finite number of missile kills in its inventory. At the same time, the threat operating in its own territory is not severely limited in the number of missiles it can fire.

A typical battle group in 2020 might consist of an aircraft carrier (CVN), one AEGIS cruiser (CG), two AEGIS destroyers (DDG), and three new destroyers (DD-X class), although given the planned reductions in the total number of ships, this composition might be optimistic. Consider the number of missile kills such a battle group might possess. The aircraft carrier would have an air wing of 60–80 aircraft. Of these aircraft, no more than 36 would typically be assigned to combat air patrol (CAP) missions. Of course, not all of these aircraft would be flightworthy at the same time. Perhaps 10% would be "down" for maintenance. Although only a fraction of the flightworthy aircraft will be airborne unless at least a half hour of early warning is given, for the purposes of this analysis, we will assume that all flightworthy CAP aircraft have been sortied. We further assume that each of the roughly 32 carrier aircraft available for CAP might be able to intercept four missiles in a massive raid. Four intercepts per aircraft are not the maximum possible. However, air-to-air loadout is likely to be six to eight AMRAAM missiles depending on whether the interceptor is an F-18 or a Joint Strike Fighter. It is unlikely that every missile will achieve a kill. It is also unlikely that an interceptor aircraft will be able to find, chase down, track, and attack more than four or five small, high-speed missiles in the 4–6 minutes that it takes the incoming missiles to close from a nominal 300-km aircraft patrol outer envelope to within the SM-2 missile range. Once SM-2 missiles can be brought to bear on the threats, the interceptors must break off the fight or risk being inadvertently shot down by our own missiles. All factors considered, four intercepts per aircraft are optimistic. Nevertheless, CAP may account for as many as 128 missile kills. It is just as conceivable that it will account for no kills. If the attack is launched from short range (within the SM-2 engagement range), CAP cannot be brought to bear unless the SM-2s are not.

Among the surface combatants, there may be as many as {128 (CG)+96 (DDG)+96 (DDG)+128 (DD-X)+128 (DD-X)+128 DD-X)} = 704 VLS cells (Baker 1998). Two-thirds of the AEGIS ship cells may contain SM-2 (214 total) and 1/8 of the DD-X cells may contain four-packs of Sea Sparrow missiles (192 total) for air defense. This is not an unreasonable loadout, given that the AEGIS ships are primarily air dominance ships and the DD-X are primarily land attack ships. Many of the VLS cells must be devoted to Tomahawk (land attack) and antisubmarine warfare missions. If any of the ships has an exo-atmospheric ballistic missile defense mission, then even fewer VLS cells will be available to carry SM-2s or Sea Sparrows. In addition to all of the missiles, the battle group may have (4+2+2+2+2+2+2) = 16 CIWS Gatling guns, each good for roughly four kills each under ideal conditions. A CIWS carries roughly 1,500 rounds of ammunition good for approximately 30 seconds of firing at the nominal 3,000 rounds per minute rate. The maximum range of the CIWS rounds is about 6,000 m, with a quoted effective of about 1,500 m. Continuous firing at an incoming subsonic missile over the range from 2,500 to 500 m (approximately 6.7 seconds) will almost certainly (but not always) result in a kill. Continued firing at targets closer than 500 m will increase the hit probability, but the probability of receiving serious damage from missile debris rises rapidly as the destruction range decreases below 500 m. In any event, CIWS is capable of only four complete 6.7 second bursts before requiring reloading. Any engagement for shorter times will have an increased probability of miss. Thus, assigning four kills per CIWS is optimistic.

The electronic warfare systems will contain a mix of some systems with passive detection, active jamming, and chaff/flare dispensers and some systems without active jamming capability. Systems with jamming will be somewhat more effective against RF-guided missiles than systems using only chaff. Both will have the same limited effectiveness against IR-guided missiles. All things considered, the EW systems may be expected to negate roughly half of those missiles that are not destroyed by the hard-kill defenses. For this analysis, assume that the antimissile missiles are 95% reliable and effective (historically, very good performance—many missiles do not perform this well). Also assume that only one missile is launched at each threat. Fleet-wide integration of the Cooperative Engagement Capability (Applied Physics Lab 1995) is assumed to support optimal weapon allocation, and so this is not unreasonable. Also assume that the aircraft and CIWS systems are 100% effective at achieving their stated number of kills. Given these weapons and assumptions, the battle group is capable of achieving at most $128+\{0.95 \times (214+192)\}+64 = 578$ hard kills with soft kills on half of the remaining threat.

A potential adversary could buy 50,000 antiship missiles over 20 years for the cost of one surface combatant per year. The access denial study (Melich et al. 2000) suggested that 1,000 missiles per attack (<2% of a near peer competitor's probable inventory and perhaps only 20% of a regional competitor's inventory) were not an unreasonably large expenditure (<US$500 million) for attacking (and almost certainly destroying) a battle group worth more than US$10 billion. In this instance, assuming that only 80% of the launched threats functioned properly, then 800 successfully launched missiles would encounter 578 hard kills and 111 soft kills. Thus, 111 missiles would survive to hit the seven ships of the battle group (16 hits per ship). Essentially all of the available defensive weapons are used up before the incoming raid can be depleted of missiles. If each CIWS were replaced by an 11-missile Sea-RAM launcher (providing roughly 103 *additional* hard kills per battle group), then 60 missiles would survive to hit the seven ships (giving eight to nine hits per ship). Even deployment of directed energy weapons (which is decades away) is unlikely to completely defeat such massive threats.

In the past, critics have argued that military forces less sophisticated than ours lack the capability to coordinate time-on-target attacks with large numbers of weapons. It is doubtful that this remains true today, but the arguments above make no reliance on temporal saturation. Even with primitive command and control systems, all threat elements could be coordinated to attack within hours of each other. As long as the weapons arrive at the target in a time frame that precludes reloading the VLS cells, the analysis is valid.

In practice, some degree of temporal saturation of the defenses due to finite defensive engagement rates and some degree of threat coordination as well as the need to fire additional missiles at those threats that were missed by the first shot would make the number of hits even larger. Doubling the size of the defensive suite would counter a 1,000-missile raid but would also add enormously to the cost. Payload costs would roughly double and each ship would have to become substantially larger to handle the increased number of missile launch cells. Of course, even the doubled defense could be defeated by 1,500-missile attacks. It will cost the adversary far less to buy more missiles and launchers/launch platforms than it will cost us to put more defensive weaponry on each of our ships, even if it were possible to put more defensive weapons on those ships, which is doubtful.

Even if the Navy was able to mount a task force with all 12 of its carrier battle groups, a 10,000 missile attack is not beyond the capability of a peer competitor and would deplete less than a fifth of that competitor's anticipated missile inventory.

The trade between offensive weapon costs and defensive weapon costs becomes even worse in the littorals. If the Navy is close enough to bombard targets on shore, weapons on shore are close enough to bombard the Navy. In addition to cruise missiles, land-based artillery (possibly with imaging seekers on maneuverable projectiles) (Gilreath et al. 1999; Lowther 1991), aircraft (including civilian aircraft with improvised armaments, armed drones, and kamikazes—manned by martyrs or remotely piloted), and small anti-armor weapons fired from "noncombatant" vessels such as small fishing boats must be considered. In short, designing to survive solely by preventing hits from occurring is a losing philosophy. Defensive weapons should not be eliminated, but they cannot be considered as the sole means of survivability.

The Navy currently lacks effective antitorpedo weapons other than decoys. Some ships carry mine hunting and mine clearing equipment, but this equipment is of questionable adequacy in addressing a major mine warfare threat. Even if improved defensive weapons for the torpedo threat and/or the mine threat become available, their incorporation into ship designs will increase costs and consume space, weight, and power, unless resources allocated to air defense are simultaneously reduced. Given the nature of the missile threat, this is unlikely, although not necessarily unwise.

Combining defensive weaponry with stealth is also not adequate. Although stealth will make many older weapons obsolete, if the adversary opts to procure an entirely new suite of weapons (with seekers guaranteed to counter the stealth incorporated into our ship designs, because they were designed after our ships were designed), then stealth will not prevent the 1,000+ missile attacks that make hit prevention a losing strategy. The threat will clearly evolve based on our own design choices, and in the course of a 40–50-year ship operational lifetime, several generations of new weapons will be designed, developed, and deployed. Because stealth and defensive weapons cannot ensure ship survivability in the future environment, we must consider designing to absorb and withstand the effects of hits.

Design for Passive Defense

We have already seen that reliance on stealth is a costly and ultimately self-defeating strategy. Sooner or later, weapons technology will overcome the stealth and the ships will become vulnerable. We have also seen that an enemy is able to easily mass more offensive weapons against any naval force than that force is possibly capable of defeating with its defensive weapons alone. Thus, neither avoiding attack nor defeating an attack can be successful by itself. The primary alternate strategy is to design our ships to take multiple hits without sustaining unacceptable levels of damage. The historical importance of passive defense to survivability is superbly demonstrated in Lillard's recent review of World War II aircraft carrier losses (Lillard 1999). Aircraft carriers with significant amounts of armor protection not only survived more hits but also took less time to return to full combat capability after those hits than carriers designed without significant armor protection.

Most current-generation antiship missiles have relatively small warheads (typically <200 kg of explosive with only a few as large as 500 or 1,000 kg). Barring an uncontrolled fire, progressive flooding, or sympathetic detonation of stored munitions, the resulting damage should be limited and the ship should be in little danger of sinking. Blast and fire damage should be confined to a few compartments, while shrapnel damage should be limited to neighboring and second neighboring compartments. Nevertheless, the ship is often rendered *hors de combat* by damage to critical equipment or controls that resided in the damaged compartments. For simplicity of expression, we will generally consider all structural design details that act to resist projectile penetration or absorb shock/blast energy as "armor." Thus, armor in various forms and amounts can serve three major protective functions: it can prevent penetration of the warhead into a compartment; it can reduce the transmission of explosive energy and explosion products into adjacent compartments; and it can limit the perforation of decks, partitions, and bulkheads by shrapnel. With limited investment in armor, one could at the very least contain shrapnel damage to those compartments penetrated by a blast. With more armor, one could contemplate limiting explosion and fire damage to the single compartment penetrated by the warhead. With thorough incorporation of armor into a design, one could envision limiting explosive warhead damage to exterior surface deformation and scorching.

Armor has not been a dominant element in warship design since World War II. The armor on a battleship was designed to withstand the armor-piercing projectiles fired by other battleships. These projectiles were mostly hardened metal cases filled with small amounts of explosives but traveling at supersonic speeds. The 2,700-pound 16 in. projectile (Iowa class battleship guns), fired with a muzzle velocity of 2,425 ft/s, contained only 41 pounds of explosive D (ammonium picrate) (Muir 1987). The armor plate expected to be encountered prevented higher explosive weight/total weight ratios. Because ships were heavily armored against guns during World War II, aircraft became the principal ship killers, capable of dropping bombs with more penetrating power (through more lightly armored decks) and considerably more explosive content than a 16 in. projectile. As a result, armor became less important than air defense weapons. Because long-range aircraft are expensive and an aircraft carrier can carry only a few dozen strike aircraft, the number of aircraft that an adversary could field to attack a fleet on the open ocean was severely limited. In addition, each aircraft could only deliver a limited number of bombs and the accuracy of delivery often depended inversely on the density of anti-aircraft fire. It was therefore practical to consider shooting down enough aircraft (or unnerving their pilots) to prevent even a single hit. This view has continued to the present day. The transition to missiles as the dominant threat did little to alter this strategy as long as engagements were anticipated to occur in blue water. This is not to say that armor was not entirely neglected in the Cold War years. Kevlar fiber armor was commonly added to aluminum superstructure warships to provide a minimum amount of protection against shrapnel and small-caliber projectile penetration (a quarter-inch aluminum plate provides very little ballistic protection compared with a quarter-inch steel plate). However, few designers considered preventing missiles from penetrating at all.

In future littoral warfare we have seen that combatants will get hit by missiles. It makes sense to resurrect the concept of "armor" as a necessary component of ship design. During the last 50 years, the army has spent considerable investment in improving armor. Using spaced armor, composite armor (fiber-reinforced and/or ceramic-based), special shaping, and even reactive armor, it is possible to defend armored vehicles against the worst anti-armor threats. It is once again feasible to consider protecting ships with armor. In a recent Capstone design project in the Naval Postgraduate School's Total Ship Systems Engineering program, the student team designed an arsenal ship (Baumann et al. 1997). To make the arsenal ship design affordable, the students opted for a modified repeat of the T-AO 201 class of oilers. After incorporating all the necessary combat systems, the ship still had excess buoyancy. As ballast, it was decided to fill the roughly 8 ft space between the double hulls of the T-AO 201 design with alternating 6 in. thick layers of concrete and polymer honeycomb material. Each 8-cell VLS unit was independently enclosed in an additional 2.5 in. of steel plate. Although detailed penetration calculations were not performed, it is likely that the external armor would completely absorb the energy released by an Exocet or Harpoon missile impact and explosion without rupture to the inner hull. Should a rupture occur (perhaps caused by one of the much larger antiship missiles with 1,000 kg or larger warheads), a high degree of thick-walled compartmentalization assured that the damage would be limited. The use of salvage foam as a last-resort damage control mechanism meant that neither fire nor flooding would progress beyond the first affected compartment. Furthermore, all critical equipment and spaces were placed in deep interior compartments. The superstructure was minimized in volume and all critical functions were duplicated in remote interior spaces. The armor around the launchers precluded a detonation in one launcher from causing sympathetic detonation in any other launcher. A joking comment about this design was that rather than the arsenal ship being a soft, high-value target that needed protection by the rest of the battle group (as feared by many), the rest of the battle group could protect itself by hiding behind the arsenal ship while it acted as an unsinkable missile sump.

Although the arsenal ship project was not limited in displacement or stressed by high mobility requirements as many future combatants will be, it should be possible to include some of the same passive protection design elements in all new designs. Composite armors incorporating metal, ceramic, fiber, and elastic layers with appropriate tilts and spacing can provide the equivalent of feet of rolled homogeneous steel armor in a fraction of the thickness and an even smaller fraction of the weight. Reductions in manpower mandated by declining budgets mean that the volume and weight formerly devoted to crew berthing, consumables' stowage, and other habitability features can be used to permit increased flexibility in compartmentalization and the increased hull and bulkhead thickness required by armor. For example, one new destroyer is anticipated to have over 12,000 tons displacement (full load) and a crew of 95. This should be compared with 9,250 tons and a crew of 354 for a DD-963 Spruance class destroyer (the values for CG-47 Ticonderoga class cruisers and DDG-51 Arleigh Burke class destroyers are within 5% of the Spruance values). The increased displacement and reduced crew should offer numerous opportunities to add armor and improve compartmentation practices. Any reduced dependence on defensive weapons and or stealth might also contribute weight, volume, and cost margin for increased armor protection.

Armor is not the only passive defense measure that might be used. The entire hull structure can be designed to damp out whipping motions induced by large explosions (from mines or torpedoes) (Department of the Navy PMS-317 1999). Magazines and other appropriate spaces can be fitted with flash suppression systems similar to those on our armored vehicles (within milliseconds of the armor being penetrated by a weapon, the compartment is flooded with a fire suppressant to minimize possibilities of secondary explosions). Magazines can be designed to vent explosions away from crew compartments and critical equipment spaces. Increased overall structural strength can prevent complete structural failure, given damage to major structural elements. With the advent of digital ships and sophisticated sensors, critical control spaces (such as the bridge or the pri-fly) do not need to be placed in the most vulnerable areas (at the outer skin of the ship). Vulnerable areas can be used exclusively for noncombat purposes such as berthing, messing, and recreation (it is assumed that ships would be at general quarters during an attack and therefore these spaces would be unmanned) and thereby provide additional "spaced armor" protection to mission critical spaces with no additional penalties. With modern sensor systems, threats can be tracked to determine the precise location of hits before they occur. Preemptive actions such as activating fire suppression systems, shutting off electrical power, and rerouting other utilities in the soon-to-be-hit spaces can significantly reduce damage, assist damage control, and speed recovery. Widely separated redundant systems can be incorporated for critical capabilities.

Ships incorporating these features may yield added benefits. Damage sustained in collisions (with other ships or underwater obstacles) may be reduced. Stronger, energy-absorbing superstructure and hull designs can minimize shock and gross structural motions that can sever cabling and piping and throw loose equipment around at considerable distances from the site of the original explosion. Armor would also provide much-needed protection against the rapidly escalating terrorist threat. No amount of defensive weaponry or stealth will protect a ship that is tied up to the pier with its defensive systems inactivated. Small to medium direct-fire weapons such as antitank missiles or indirect-fire weapons such as mortars can inflict serious damage on current combatants. Although reasonable thicknesses of shipboard armor cannot completely stop large, shaped-charge warheads, they can limit the damage to a portion of the single compartment that is ultimately penetrated. They may also be capable of completely stopping smaller conventional mortar rounds (with antipersonnel warheads) from doing more than cosmetic damage. A large truck bomb detonated on a pier next to a conventional warship could result in the obliteration of much of the ship's superstructure. Repair of such damage would take months and could cost almost as much as a new ship. Increased armor and the resulting blast hardness would minimize the damage such a bomb could cause, possibly limiting that damage to masts and exposed sensors and weapons.

Clearly, one cannot rely entirely on passive defense for survivability. Enough ordnance delivered against a concentrated target will ultimately destroy it. However, we have already seen that stealth and active defense cannot provide the survivability needed. Thus, future combatants must combine the best in active defense (incorporating directed energy weapons at the earliest practical time—directed energy is the only weapon with a virtually unlimited number of kills, although the kill rate is still limited but high) with a significant level of stealth (enough to force threat missile designers to use more sophisticated and expensive seekers) and a major amount of passive defense (enough armor to completely negate the smaller antiship missiles).

Design for Quantity

Referring to military hardware, Joseph Stalin once said "Quantity has a quality all its own." Although he was referring to the fact that large numbers provide the ability to concentrate firepower against an enemy's weak points, the statement is also true in the defense. In the 1990s, with force transformation becoming a necessity, the fourth survivability strategy of increased numbers was investigated in a number of projects. One of these, originally called "Streetfighter," involves replacing a small fleet of large, high-capability ships with a large fleet of small, modest-capability ships with fleet-integrated capability equal in both cases (Hughes 1995). This and other large-quantity ship concepts were pursued under the auspices of the Naval Warfare Development Command. These included the "Sea Lance" access assurance craft (Harney 2001) and the "Sea Archer" unmanned air vehicle aircraft carrier (Calvano et al. 2002). Survivability comes from large numbers, small size, and high maneuverability. The threat will simply not be able to target and hit them all.

A smaller size automatically reduces observability, although this may not be a significant contributor to survivability unless size reduction is carried to extremes. High speed and high maneuverability will also make a craft harder to hit, although against supersonic, multi-g-capable missiles with precision terminal seekers, the extra speed and maneuverability that can be achieved by smaller ships is not likely to have a significant effect. However, increased numbers can have at least two significant effects.

First, a single large ship may require multiple hits (M) to be rendered ineffective, while a small ship may require only one. However, N small ships require a total of at least N hits to be rendered completely ineffective. If N is significantly larger than M, then survivability improves by having many smaller ships. If the small ships can survive one or more hits, the survivability margin of small ships over large ships becomes even larger. Second, targeting is likely to have a random element. It is unlikely that every missile will be targeted in advance at a specific ship and it is unlikely that the ships will be targeted uniformly. Doing so requires a degree of coordination and real-time tracking knowledge that is probably not achievable. As a result, with a few large ships, some will be attacked by more missiles than the average (which is likely to be quite high) while some will be attacked by fewer missiles. With many smaller ships, the average number of missiles per ship will be significantly reduced, but the variance may not be decreased appreciably. Some ships will receive an overwhelming concentration of missiles while others may receive a few or none. Some ships will almost certainly be lost, but some will almost certainly survive.

Increased numbers may be even more effective against the submarine threat and the mine threat. Submarines will necessarily be available in orders of magnitude smaller quantities than missiles. Furthermore, submarines carry at most a limited number of antiship weapons (i.e., potential kills). Mines may be deployed in large numbers, but given the mobility of ships, mines cannot be maneuvered or deployed for mass attacks. The number of mines in any single transit lane will be limited and possibly less than the number of ships. Some ships will invariably make it through any minefield.

Losses in combat that will invariably occur may be made somewhat more palatable by reduced manning. Essential life cycle cost reductions will cause manning to be reduced to levels well below the current standards. If a cultural change were to make it acceptable to lose ships (if the crews can be saved) in the same way that air forces accept loss of aircraft, then manning could be reduced to 10–20% of the current levels. The elimination of personnel for damage control makes this possible. In the extreme, the increase in numbers could be obtained by deployment of unmanned surface vehicles. Loss of unmanned assets does not carry the emotional baggage associated with the loss of crewed ships.

It is generally accepted that one large ship is cheaper than two smaller ships of comparable aggregate capability. This has partially justified the trend toward larger displacement ships that has prevailed for the last century (if not longer). However, a single large ship can only be in one place at a time. Not all missions require the total capability of the larger ship. Many could be performed by the capabilities of a much smaller ship. Several such ships could perform several different geographically distributed missions at the same time, while retaining the ability to perform the few major missions if brought together in a task force. Once rendered inoperable or sunk, the single large ship cannot perform any missions—no capability remains. If one smaller ship is sunk, the remainder can perform all of their normal missions, and can still generate an aggregate albeit somewhat reduced capability to perform a more major mission. Given that a single large ship will almost certainly be destroyed in a massive engagement, the increased cost of multiple smaller ships, some of which are likely to survive, becomes a good investment.

Significantly reduced size does not mean loss of capability. In the past, air defense and antisubmarine warfare have been performed by frigates and corvettes. Naval fire support is performed with surface-to-surface missiles and/or 5 in. guns and these can be carried on small combatants. Even naval aviation can operate from platforms as small as 5,000 tons displacement. Conventional take-off and landing aircraft cannot be accommodated, but short take-off vertical landing (STO/VL) aircraft can. In the future, unmanned air vehicles will likely take over more and more of the missions currently performed by manned aircraft. Thus, a significantly reduced size does not mean loss of capability, but it will entail changing the way we perform some missions.

Conclusions

The changing nature of the threat and the anticipated changing nature of Navy missions will place naval combatants into conditions more hostile than the Navy has seen since World War II and quite different from those envisioned in the Maritime Strategy. The threat will be capable of using weapons in quantities and qualities that can overwhelm defensive weapon systems. Incorporation of stealth into ship designs will not eliminate this eventuality, although it will make it somewhat more expensive for the enemy to field the overwhelming force. However, it will almost certainly make our ships prohibitively expensive to procure. Regardless, in full-scale conflicts in the post-2020 time frame, naval combatants can expect to be hit by antiship missiles (and mines and torpedoes) in substantial numbers. Ships designed to current survivability practices with significant defensive weaponry and stealth design will not survive. Future combatants must be designed to take multiple hits (dozens) and not only survive but also be able to continue to fight. We cannot afford to ignore defensive weaponry and we must incorporate a significant degree of stealth, but survival will require designs that are resilient to hits. We must resurrect armor concepts (in their most current and innovative incarnations) and we must pay more attention to functional redundancy, functional location, and compartment design for survivability. In the words of Admiral of the Fleet Lord Chatfield (British CinC of the Atlantic and Mediterranean Fleets, 1929–1932), "Ships are built to fight, and must be able to take blows as well as to inflict them" (Brown 1991). We should also consider building many smaller ships rather than a few larger ships. At least some of these should be unmanned. A balanced approach between stealth, defensive weaponry, passive defensive design, and more numerous smaller platforms is needed if warships are to be both survivable and affordable in the post-2020 time frame.

Acknowledgments

The author wishes to acknowledge many helpful discussions with Professor Charles Calvano (Captain, USN [Ret]) of NPS concerning ship survivability and to thank Professors Michael Melich and Patrick Parker for inviting him to participate in the Enemy Area Denial System Red Team study. The views and opinions in this paper are those of the author. They do not necessarily represent those of the Naval Postgraduate School, the US Navy, or the United States Government.

References

Applied Physics Laboratory Staff, "The cooperative engagement capability," *Johns Hopkins APL Technical Digest*, Vol. 16, No. 4, pp. 377–396, 1995.

Baker III, A.D., *The naval institute guide to combat fleets of the world, 1998–1999*, Naval Institute Press, Annapolis, 1998.

Baumann, G., C. Calvano, M. Chase, and G. Null, "An arsenal ship design," *Naval Engineer's Journal*, Vol. 109, No. 6, pp. 85–94, 1997.

Brooks, L.F., "Naval power and national security," *International Security*, Vol. 11, No. 2, pp. 58–88, Fall 1986.

Brown, D.K., *The future British surface fleet: options for medium-sized navies*, Naval Institute Press, Annapolis, 1991, p. 71.

Calvano, C., D. Byers, R. Harney, F. Papoulias, J. Ciezki, R. Ashton, LT J. Keller USN, LCDR R. Cooke USN, CDR(sel) J. Ivey USN, LT B. Stallings USN, LT A. Dalakos (Hellenic Navy), LT S. Searles USN, LTJG O. Okan (Turkish Navy), LTJG M. Gokce (Turkish Navy), LT R. Kuchler USN, LT P. Lashomb USN, and I. Ng (Singapore MOD), "'SEA ARCHER': Distributed Aviation Platform." Naval Postgraduate School Report NPS-ME-02-01, January 2002. Available at http://www.nps.edu/academics/gseas/tsse/docs/projects/2001/report.pdf, accessed July 14, 2010.

Defense Science Board, "Investments in 21st century military superiority," Summer Study, 1995.

Department of the Navy PMS-317, "Not your father's gator." This is a digital video (on CD-ROM) produced by the LPD-17 program office, June 1999.

Federation of American Scientists, "Military Analysis Network." 2009. Available at http://www.fas.org, accessed July 14, 2010.

Gilreath, H.E., A.S. Driesman, W.M. Kroshl, M.E. White, H.E. Cartland, and J.W. Hunter, "Gun-launched satellites," *Johns Hopkins APL Technical Digest*, Vol. 20, No. 3, pp. 305–319, 1999.

Harney, R.C., "Sea lance ensures access to the littorals," *U. S. Naval Institute Proceedings*, Vol. 127, No. 10, pp. 96–98, 2001.

Hughes Jr., W.P., "A salvo model of warships in missile combat used to evaluate their staying power," *Naval Research Logistics*, Vol. 42, pp. 267–289, 1995.

Lillard, J., "Austerity is not affordable," *U. S. Naval Institute Proceedings*, Vol. 125, No. 8, pp. 38–42, 1999.

Lowther, W., *Arms and the man: Dr. Gerald Bull, Iraq, and the supergun*, Presidio Press, Novato, 1991.

Mahnken, T.G., "Deny U.S. access?," *U. S. Naval Institute Proceedings*, Vol. 124, No. 8, pp. 36–39, 1998.

Melich, M., P. Parker, and E.A. Smith Jr., "The planner's dilemma: innovation, technological change, and long-range planning," *Naval Postgraduate School Research*, Vol. 10, No. 2, pp. 4–5, 41,42 2000.

Muir, M., *The Iowa class battleships*, Sterling Publishing, New York, 1987, pp. 140–143.

Office of the Chairman of the Joint Chiefs of Staff, "Joint Vision 2010." July 1996.

Office of the Chairman of the Joint Chiefs of Staff, "Concept for future joint operations: expanding Joint Vision 2010." May 1997.

Palmer, M.A., "A history of the U. S. Navy." Department of the Navy, Naval Historical Center, December 19, 1996. Available at http://www.history.navy.mil/history/history4.htm, accessed July 14, 2010

U. S. Government Accounting Office, "B-2 bomber: cost and operational issues." GAO/NSIAD-97-181, August 1997.

Watkins, J.D., "The maritime strategy," *U. S. Naval Institute Proceedings*, Vol. 112, Suppl, pp. 3–17, January 1986.

Author Biography

Dr. Robert C. Harney is an Associate Professor of Systems Engineering at the Naval Postgraduate School. He teaches combat systems courses in the Total Ship Systems Engineering program and conducts research in ship design, survivability, and counter-proliferation of weapons of mass destruction. Before joining NPS, he spent over two decades in technical and management positions developing advanced sensors, weapons systems, and countermeasures at national laboratories and in the defense industry.