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Assessing Aegis Program Transition to an Open-Architecture Model

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Summary

Background

Aegis is a highly integrated combat system with anti-air warfare, ballistic missile defense, surface, subsurface, and strike roles that the U.S. Navy has installed on 84 of its ships. While the Navy wants to maintain the Aegis system as the preeminent combat system for surface combatants, this is an expensive and time-consuming endeavor. To reduce costs and enable the use of rapidly evolving commercial computing technology, the Navy is transitioning Aegis to use open-architecture (OA) software, a common source library (CSL), and commercial off-the-shelf (COTS) processors, taking advantage of their 18- to 24-month replacement cycle.

The Navy's transition from its legacy business model to the new integrated warfare systems (IWS) business model[1] may introduce new challenges and risks for the fleet and enterprise that develop and field the Aegis weapon system (AWS).[2] Under the legacy business model, the AWS used proprietary software operating on military-specification computing hardware. Upgrades to the AWS were developed every five to six years and fielded only to new-construction ships and those receiving a midlife upgrade. The IWS business model will

1 The IWS business model is articulated in the Program Executive Office (PEO) Integrated Warfare Systems Acquisition Management Plan (2013).

2 AWS refers specifically to the computer software and hardware, radar system (SPY-1), and vertical launch system onboard an Aegis ship. The additional sensors, communication systems, weapons, and countermeasures are part of the broader Aegis combat system (ACS).

use OA software operating on COTS computing hardware and will involve periodic upgrades for all ships, both new and in-service. The plan is to upgrade software through advanced capability builds (ACBs) every four years, independently of computing hardware upgrades, called technology insertions (TIs), which will occur every four years, with individual ships receiving every other upgrade.

The introduction of new capabilities into the Aegis fleet is likely to quicken over the next decade due to ballistic and cruise missile defense requirements. The Aegis fleet is the backbone of the U.S. Navy's surface fleet and will remain so for decades. Thus, it would be particularly detrimental to install improperly designed or tested combat systems on this fleet.

Purpose

This report focuses on issues related to the development, integration, and testing of upgrades to the AWS. Specifically, it attempts to answer the following three questions:

- How does the Navy currently develop, test, and field upgrades to the AWS, and how will that process change under the IWS business model?
- How does the IWS business model affect AWS modernization and fielding rates in terms of both the technical infrastructure and fleet capabilities?
- What modernization rate under the IWS business model should be recommended to the Navy to balance fleet capability, risk, and cost?

The IWS business model for managing the acquisition of Aegis upgrades has four critical components. First, the model periodically distributes capability upgrades to both new and in-service ships using concurrent development and sequential integration and testing (I&T). Second, the model improves the efficiency of weapon system development and support by using modern software engineering processes that enable continuous development rather than the sequential process used under the legacy business model. Third, the model fosters competition by allowing the Navy to seek bids from multiple commercial vendors for developing individual components of the weapon system software. Finally, the model allows the Navy to leverage points of overlap in capability development across weapon systems. For example, each weapon system has a software component that manages detected threat tracks (a so-called "track manager"). Under the legacy business model, track managers were developed and implemented separately, but under the IWS business model, a single track manager would be available to all systems.

The OA character of the IWS business model promises substantial benefits[3] by allowing improvements to propagate across the Aegis fleet, introducing enhancements more quickly, and providing greater computing capabilities. However, moving from the legacy business model to the OA-based IWS model while maintaining a demanding operational schedule is challenging. The software and hardware upgrades to support the IWS business model must be installed across the entire Aegis fleet. The Navy is modernizing only three to four ships per year, with each ship upgrade requiring between 48 and 52 weeks. Thus, the Navy must maintain its legacy AWS for over 20 more years.[4] Further, the Missile Defense Agency's ballistic missile defense (BMD) program will have to find a place in the hardware and software schedules dictated by the OA plan. Finally, OA requires its own development, integration, and testing, which must occur at a faster pace than the historical norm for the Aegis program. Taken together, these factors make for complicated development, integration, and fielding activities.

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[3] OA enables software components to work across a range of commercial computing hardware and interoperate with other software components.

[4] By law, ships within five years of their decommissioning date do not receive upgrades. All ships in the fleet after 2036 will be upgraded to the OA ACS.

Research Approach and Limitations

We used a multi-pronged approach to address our study questions. First, we conducted semistructured interviews with industry and government representatives from the Aegis enterprise, including the PEO IWS, Lockheed Martin, the Aegis Technical Representative (Aegis TECHREP), the Naval Surface Warfare Center (NSWC) Dahlgren Division, the NSWC Port Hueneme Division, the NSWC Corona Division, the Surface Combat Systems Center (SCSC), and the Combat Systems Engineering Development Site (CSEDS). These interviews focused on characterizing the legacy approach to developing, fielding, and supporting the AWS and on understanding each representative's view of how the IWS business model might affect the enterprise.

Second, we interviewed industry and government representatives from the Acoustic Rapid COTS Insertion (ARCI) and Ship Self-Defense System (SSDS) enterprises, including Raytheon and PEO Submarines. These interviews focused on understanding lessons learned from ARCI's and SSDS's unique experiences in transitioning to an OA-based approach.

Third, we collected historical workforce and facility usage data from key organizations and facilities in the Aegis enterprise. These data allowed us to characterize the historical effort involved in developing, integrating, and testing legacy baselines and ACBs and provided a basis for characterizing the choices and trade-offs involved in transitioning to the IWS business model.

Fourth, we developed a simulation model to estimate the effect of both the IWS business model and the Aegis modernization rate on the fleet. The simulation model allows the rate of software and hardware upgrades to vary independently of each other. In the context of this report, *drumbeat* refers to the periodicity of an update. For example, a software update drumbeat of two years means that PEO Integrated Warfare Systems develops and fields an AWS software upgrade every two years. Additionally, the model allows individual ships to receive either every upgrade or every other upgrade.

Finally, we developed a spreadsheet model to estimate the technical infrastructure required to develop, integrate, and test AWS upgrades. Using Naval Surface Warfare Center (NSWC) and prime contractor data on personnel, facility usage, and cost, we applied the model under varying assumptions regarding upgrade drumbeats and level of effort.

Our analysis of implications of the Navy's plan requires us to make various assumptions about, for example, the stability of funding for Aegis, shipbuilding plans and schedules, and ship availabilities for weapon system modernization and upgrades, among other issues discussed below. We based these assumptions on the most current Navy plan for modernization, shipbuilding, and upgrades at the time of our writing. In reality, however, future funding is unknowable, ship availabilities change routinely, and the expense of upgrades depends on countless factors outside the scope of our analysis. While we do not expect our findings to depend on minor changes to these parameters, we discuss potential risks below.

This report focuses on the development, integration, testing, and fielding of periodic updates to the Aegis fleet under the proposed IWS business model. Decisions made by the Navy in implementing the model will strongly affect Aegis training resources. Training resources—including instructors, equipment, and laboratory space—are limited and could constrain implementation. However, this report does not assess the impact of the IWS business model on Aegis training resources.

How the Legacy Business Model Differs from the IWS Business Model

The legacy and IWS business models differ substantially. Since its inception, the Aegis program has fielded a new version of the baseline system every five to six years. Under the legacy business model, a ship receives an initial AWS baseline and, potentially, an updated version at the midlife upgrade.[5] The IWS business model, by contrast, allows soft-

[5] Many surface combatants enter the shipyard at the midpoint in their expected service life to receive updates to their installed hull, mechanical, electrical, and combat systems.

ware and hardware improvements to be introduced on any modernized Aegis ship (i.e., one that has had both ACBs and TIs). Under this plan, a new ACB and TI are developed every four years. Individual Aegis ships receive every other upgrade. The IWS plan substantially alters the performance characteristics of the fleet. Once the AWS reaches a steady state (in approximately 2028), it will take about 7.5 years to install a given software upgrade across the entire fleet. Table S.1 compares the fleet attributes under the IWS and legacy business models.

The two business models also present different cost implications. As mentioned, the legacy business model involves installing an initial capability during construction, with one subsequent upgrade. Since individual ships receive no further upgrades, they incur no further fielding costs, and the capability remains as it is. Under the IWS business model, ship software and hardware is continually upgraded. Each upgrade incurs cost, both for the hardware itself and for the team required to install the upgrade.

However, the IWS business model also produces some cost efficiencies. Under the legacy model, each upgrade is installed on about 21 percent of the fleet; under the IWS business model, each upgrade reaches 96 percent of the modernized fleet. Essentially, development costs are spread across four times as many ships. Also, systems that depend on commercial hardware and software tend to have significantly lower initial installation costs.

But the IWS business model carries with it several sources of risk. The most basic risk stems from the fact that the plan differs fundamentally from the legacy business model in how it develops and fields capa-

Table S.1
Estimated Fleet Attributes Under the Legacy and IWS Business Models

Model	Software Upgrades per Year (average)	Hardware Upgrades per Year (average)	Hardware-Software Combinations in Fleet	Software Age (years)		Hardware Age (years)	
				Max.	Avg.	Max.	Avg.
Legacy			4.5	25.6	14.0	25.6	14.0
IWS	18.7	9.3	4.0	8.7	6.2	12.7	8.0

NOTE: Legacy data not available for blank cells.

bility upgrades. The Navy's use of the ARCI program for its submarine combat systems and the SSDS for aircraft carriers provides some related institutional experience and lessons learned, but Aegis differs from those programs in critical ways. Thus, the Navy should expect a uniquely complex fielding experience, proceed slowly when implementing this plan, and be prepared to derive its own lessons learned as it fields periodic upgrades to modernized ships and develops these upgrades from a CSL.[6]

Other sources of risk include the fact that multiple government stakeholders may have a vested interest in the legacy business model; the complexity of managing a CSL; the possibility that the Navy and the BMD program will compete for a limited pool of technical personnel, facility time, and access to the CSL; and the diversion of resources to the CSL from direct capability improvements.

The Navy can mitigate some of these risks by making capital investments in the CSL and software componentization, delaying investments in product-line development until the transition to the CSL is successful, streamlining government involvement in I&T to reduce schedule risk, enforcing requirements discipline, staggering TIs and ACBs, and harvesting lessons learned from ARCI and SSDS.

Effects of the IWS Business Model on Aegis Modernization and Fielding Rates

Generally speaking, the IWS business model improves Aegis fleet capabilities by spreading individual upgrades to all or parts of the fleet. That said, the Navy's PEO for Integrated Warfare Systems, working with the fleet and the Office of the Chief of Naval Operations, can make policy choices that affect both the infrastructure required for Aegis development and the capabilities delivered to the fleet. It can choose the rate (referred to in this report as a "drumbeat") at which periodic

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[6] The CSL is a master library that stores the code for all the Aegis applications and allows the Navy to develop several software components concurrently that can then be propagated to the fleet.

software and hardware upgrades occur. It can also decide whether ships will receive every upgrade or every other upgrade. Additionally, it can choose to field ACBs and TIs simultaneously or to stagger them. We developed a model to assess the effects of these various decisions.

Drumbeat Decisions

We explored the effects of two-, four-, and six-year drumbeats for ACB and TI insertions. Additionally, we analyzed the effects of giving ships every upgrade versus every other upgrade. Table S.2 compares the effects of the drumbeats examined for the IWS business model with those of legacy practices in terms of average and maximum age of software and hardware.

Under the IWS business model, more of the fleet has newer software and hardware. The average age of these components under the legacy business model is 14 years, and the maximum age is almost 26 years. With a drumbeat of six-year insertions under the IWS business model, these ages drop to just under seven years and almost nine years, respectively. This also means that ACBs and TIs do not stay in the fleet as long as they do under the legacy business model. Thus, there are fewer Aegis versions in the fleet to support under the IWS model. Under the legacy business model, an average of 4.5 Aegis versions are deployed in the fleet at a given time. Meanwhile, under IWS model, an average of only two are deployed. Thus, IWS lowers the average age of the technology present in the fleet and brings that technology closer to the industry's current hardware obsolescence cycle.

If the drumbeat quickens to four-year insertions, the maximum age declines from nine years to six, and the average age declines from

Table S.2
Effects of Different Drumbeats on the Average and Maximum Ages of Hardware and Software

Age of Hardware and Software (years)	Legacy Business Model	IWS Business Model		
		6-Year	4-Year	2-Year
Average	14	7	5	< 3
Maximum	26	9	6	> 3

seven to five. If the drumbeat quickens even further—to two-year insertions—the maximum age drops to just over three years and the average age to just under three years. However, speeding up the insertions means that more ships are upgraded each year. At a drumbeat of six years, 11 ships per year receive upgrades, but with a drumbeat of two years, that number climbs to 34. This increase has important implications for the Navy's ability to make sufficient ships available for upgrading and for training crews in the new concepts.

Upgrade Decisions

The difference in the effects of getting every upgrade versus every other one out to the fleet is also significant. For example, when the ACB drumbeat is two years but a ship receives only every other upgrade, the average age of the software increases from three to four years, and the maximum age increases from just over three to just over five years. Also, the average number of hardware-software combinations deployed in the fleet rises from 2.6 to 5.5.

The current IWS business model calls for four-year software and hardware upgrades, with ships receiving every software upgrade and every other hardware upgrade. This results in individual upgrades being installed on about 43 percent of the fleet (better than legacy business model results of 21 percent), but the process would be about half as efficient if ships were to get every upgrade. The model calls for installing hardware on eight ships and software on 17 ships per year. This actually increases the number of hardware-software combinations in the fleet, which will likely increase in-service support costs and interoperability issues.

Implications for Development

As the Navy considers alternative upgrade intervals, it must balance upgrade size and frequency. Smaller, more frequent upgrades will distribute capability improvements across the fleet more quickly but will mean that the fixed costs of I&T will consume more of the fixed IWS budgets. Larger, less frequent updates will distribute capability more slowly but will result in the fixed costs of I&T consuming less of the fixed IWS budgets.

The choice of TI intervals requires the additional consideration of coordinating computing and networking hardware upgrades with the industry that produces the COTS equipment. ARCI has upgraded its hardware roughly every two years, which allows it to minimize procurement and in-service costs while leveraging recent, if not state-of-the-art, COTS equipment. Integrating new hardware every two years would be especially challenging for Aegis. However, the Navy may be able to mitigate the in-service cost of slower drumbeats by warehousing retired computing hardware and using the parts as spares. To date, Aegis has not needed the computing capacity that would be provided by more frequent upgrades.

Recommended Modernization Rate

We agree with the current IWS plan to field ACB and TI upgrades on a four-year drumbeat. In our proposed implementation approach, every ACB and TI upgrade is installed on every Aegis ship over the four-year period. Further, the ACB and TI upgrades are offset by two years. Figure S.1 illustrates this proposed approach. In addition to new computer hardware, TI upgrades include software fixes in response to computer program change requests (CPCRs) identified during the preceding ACB, as well as modifications to the AWS required to support ACS upgrades. For example, TI-18 would include software fixes identified by the fleet operating with the ACB-16 upgrades. Table S.3 shows the fleet attributes under three models: legacy, IWS, and RAND.

Why Four Years for ACB?

We recommend a four-year ACB drumbeat to balance the desire to deploy new capabilities with the risk of compressed I&T times and the disruption of each ship's operations. Aegis historical development indicates that a faster drumbeat would be difficult to execute. Furthermore, a faster rate would devote a prohibitively large fraction of Aegis technical resources to I&T and constrain development efforts critical to providing mature technology for subsequent ACBs. Finally,

Figure S.1
RAND's Proposed ACB/TI Implementation

<table>
<tr><th></th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th></tr>
<tr><td>ACB</td><td colspan="4">ACB-12</td><td colspan="4">ACB-16</td><td colspan="4">ACB-20</td></tr>
<tr><td>TI</td><td colspan="2">TI-12</td><td colspan="4">TI-14</td><td colspan="4">TI-18</td><td colspan="2">TI-22</td></tr>
<tr><td>Ship #1</td><td colspan="4">ACB-12/TI-12</td><td colspan="4">ACB-16/TI-14</td><td colspan="4">ACB-20/TI-18</td></tr>
<tr><td>Ship #2</td><td colspan="2">Legacy</td><td colspan="4">ACB-12/TI-14</td><td colspan="4">ACB-16/TI-18</td><td colspan="2">ACB-20/TI-22</td></tr>
</table>

RAND *RR161-S.1*

the planned capabilities in the Aegis technology roadmap fit easily into four-year cycles.

Why Four Years for TI?

The I&T burden for TI is considerably lower than for ACB. The TI drumbeat must support the computing power required by the ACB capabilities. Normally, this would suggest a faster TI drumbeat than ACB drumbeat, but the current suite of ACB upgrades does not require all of the additional computing power offered by the switch to com-

Table S.3
Fleet Attributes Under Three Plans

Model	Software Upgrades per Year (average)	Hardware Upgrades per Year (average)	Software-Hardware Combinations in Fleet	Software Age (years)		Hardware Age (years)	
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Legacy			4.5	25.6	14.0	25.6	14.0
IWS	18.7	9.3	4.0	8.7	6.2	12.7	8.0
RAND	18.7	18.7	3.0	8.7	6.2	8.3	6.2

NOTE: Legacy data not available for blank cells.

mercial hardware. Furthermore, installing new commercial hardware on the required number of ships under the IWS business model is expensive. A four-year drumbeat minimizes the potential risks inherent in deviating from the commercial cycle. Also, including software fixes in each hardware upgrade increases opportunities to improve the stability of the Aegis code, respond to issues identified by operators, and improve training stability.

Why Stagger Insertions?

Offsetting the four-year ACB and TI cycles balances deployed capabilities and development risk and offers three advantages. First, it isolates software and hardware development efforts from one another. Installing upgraded software on mature hardware enables the rapid identification of issues in either the hardware or software. Second, this approach incorporates software fixes in both the software and hardware upgrades, doubling the opportunities to incorporate such fixes and support ACS element upgrades. Third, this approach allows the Navy to level-load the demand on the Aegis technical infrastructure.