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THESIS

DDG-1000 MISSILE INTEGRATION: A CASE STUDY

by

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March 2014

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13. ABSTRACT (maximum 200 words)

This thesis is a case study that examines missile development and integration for the DDG-1000 program. In particular, it analyzes various programmatic decisions through the lens of systems engineering standards, articles in scholarly journals, established government acquisition guidelines, and case studies of government and commercial engineering projects. Four risks were identified. First, failure to establish top-level requirements that reflect DDG-1000 specific needs introduces the potential for the missiles to fail performance or safety evaluations. Second, late requirement changes imposed by the government increase the potential for costly rework and schedule delays if integration issues surface during testing. Third, a "use as is" decision (meaning that legacy missile requirements were applied to the DDG-1000 missile effort) could result in an inadequate system architecture and/or late identification of system incompatibilities. Finally, organizational and funding issues have hampered the establishment and efficiency of engineering change control and integration management. The thesis recommends: that DOD acquisitions continue to emphasize and enable rigorous application of system engineering early in the acquisitions process; that all programs perform a thorough flow-down of requirements even if utilizing legacy systems; and that all funding for weapon development be placed in the control of the Program Executive Office for Integrated Warfare Systems.

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DDG-1000 MISSILE INTEGRATION: A CASE STUDY

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ABSTRACT

This thesis is a case study that examines missile development and integration for the DDG-1000 program. In particular, it analyzes various programmatic decisions through the lens of systems engineering standards, articles in scholarly journals, established government acquisition guidelines, and case studies of government and commercial engineering projects. Four risks were identified. First, failure to establish top-level requirements that reflect DDG-1000 specific needs introduces the potential for the missiles to fail performance or safety evaluations. Second, late requirement changes imposed by the government increase the potential for costly rework and schedule delays if integration issues surface during testing. Third, a "use as is" decision (meaning that legacy missile requirements were applied to the DDG-1000 missile effort) could result in an inadequate system architecture and/or late identification of system incompatibilities. Finally, organizational and funding issues have hampered the establishment and efficiency of engineering change control and integration management. The thesis recommends: that DOD acquisitions continue to emphasize and enable rigorous application of systems engineering early in the acquisitions process; that all programs perform a thorough flow-down of requirements even if utilizing legacy systems; and that all funding for weapon development be placed in the control of the Program Executive Office for Integrated Warfare Systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

AE	acquisition environment
AFSS	Advanced Fire Suppression System
AGS	Advanced Gun System
AMDR	Air & Missile Defense Radar
ASCM	anti-ship cruise missile
ASW	anti-submarine warfare
BUR	bottom-up review
CDR	critical design review
CEU	canister electronic unit
CG	guided missile cruiser
CONOP	concept of operations
CNO	Chief of Naval Operations
C/S	combat system
CSB	configuration steering board
DAS	Defense Acquisition System
DAWIA	Defense Acquisition Workforce Improvement Act
DBR	Dual Band Radar
DDG	guided missile destroyer
DOD	Department of Defense
ERGM	Extended Range Guided Munition
ESSM	Evolved SeaSparrow Missile
FCS	Future Combat System
GAO	Government Accountability Office
ICD	interface control document
ICWI	interrupted continuous wave illumination
IPS	Integrated Power System
IUWS	Integrated Undersea Warfare System
IWS	Integrated Warfare Systems
JUWL	Joint Universal Weapon Link
LCS	littoral combat ship

LSI	lead system integrator
LRLAP	Long-Range Land Attack Projectile
MFR	Multi-Function Radar
NGFS	naval gunfire support
NSFS	naval surface fire support
ORD	operational requirements document
OSD	Office of the Secretary of Defense
OT&E	Operational Test and Evaluation
PARCA	Performance Assessments & Root Cause Analysis
PDR	preliminary design review
PEO	Program Executive Office
P_k	probability of kill
PVLS	Peripheral Vertical Launch System
QDR	Quadrennial Defense Review
RIDS	Raytheon Integrated Defense Systems
R&D	research and development
RMA	revolution in military affairs
RMS	Raytheon Missile Systems
SC-21	Surface Combatants for the 21st Century (Study)
SENV	system environment specifications
SM	Standard missile
SPD	specified performance documents
SYS	system performance specifications
TLR	top level requirements
TSCE	Total Ship Computing Environment
USN	United Stated Navy
USD AT&L	Undersecretary of Defense for Acquisition, Technology & Logistics
VLS	vertical launch system
VSR	Volume Search Radar
WSARA	Weapons Systems Acquisition Reform Act

EXECUTIVE SUMMARY

This thesis is a case study that examined missile development and integration for the DDG-1000 program. It describes the strategic situation that spurred the initial DDG-1000 concept and how the program has changed in size and scope over time. It also describes combat system development for the ship, particularly the Dual Band Radar and the Joint Universal Weapon Link (JUWL), which allows SM-2 and ESSM missiles to be employed by the class. It analyzed various DDG-1000 programmatic decisions through the lens of systems engineering standards, articles in scholarly journals, established government acquisition guidelines, and case studies of government and commercial engineering projects.

DDG-1000 was an outgrowth of the "Revolution in Military Affairs" (RMA) philosophy that gained prominence immediately following the First Gulf War. The RMA specifically advocated developing and fielding the most technologically advanced systems possible so that U.S. and allied forces could gain overwhelming dominance on the battlefield. Developing multiple such technologies and installing them simultaneously into a new ship class runs counter to the mindset that guided previous ship and submarine advancements. Historically, new combatants utilized "tried and true" technologies in most areas while featuring two or three significant improvements. Hence risk to the new class was limited. The commonality of hull, mechanical and electrical and combat systems (C/S) between the DD-963, FFG-7, CG-47, and DDG-51 class are an example of this approach. When successful systems were introduced and operationally tested (such as gas turbine propulsion), they were incorporated into future classes. Similarly, C/S advancements could be retro-fitted into previous classes (such as CG-47 vertical launch systems were retro-fitted into the DD-963 class).

Conversely, the Navy had experienced substantial problems in developing multiple advanced technologies for the Seawolf class submarine. The costs of the effort were so substantial, in fact, that Congress truncated the program. The Air Force's B-2 bomber program encountered similar problems and met a similar fate. Nevertheless,

DDG-1000 proceeded with this risky development strategy. The results were much the same as the B-2 and Seawolf.

Missile development for DDG-1000 took the opposite approach. “Legacy” missiles were designated for incorporation into DDG-1000 under the assumption that minimal modifications to the missiles would be necessary. But this decision may prove to be a mistake because the radar and combat systems that will be used to employ the missiles are completely new and the legacy missiles may require significant changes to function with the new systems. The interfaces between the missile, the combat system, and the radar are critical to achieving desired performance. Because the ship, combat system, radar, and missile variants are still in development, it is not possible to give an unequivocal or complete analysis of their performance. However, we can analyze the effort in terms of risk and lessons learned from prior case studies. The analysis of missile development conducted for this thesis identified four main risks.

First, failure to establish top level missile requirements that reflect DDG-1000 specific needs introduced the potential for the missiles to fail performance or safety evaluations. DDG-1000 has a different mission, different operating environment, and different threat set than the platforms the SM and ESSM were designed to protect. Failure to establish new requirements means that there will be no way to truly assess the performance of the missiles in comparison to their legacy version.

Second, late requirement changes imposed by the government increased the potential for costly rework and schedule delays if integration issues surface during testing. The Navy originally directed the use of the SM-2 Block III-B missile for DDG-1000. In 2012, several years into the project, the III-B missile was replaced with the Block III-A version. The missiles are not identical and their performance differences have already prompted software changes in the radar and introduce additional risk that other differences will not be captured before operation testing.

Third, a “use as is” decision regarding missile interfaces was made early in the development effort. In essence, the only new requirements given to the ESSM and SM missile design team related to the development of a new ship-to-missile weapon link on a new frequency. All other requirements, such as pre- and post-launch interfaces, electromagnetic vulnerability requirements, and so on, were carried forward from the legacy Aegis variants of the missiles. This "use as is" decision could result in inadequate system architecture, late identification of system incompatibilities, or both. It is a certainty that the mechanical and electrical environment of DDG-1000 will differ from the DDG-51 and CG-47 classes–it only remains to be seen if the differences have adverse effects on missile performance or safety. Late identification of such issues could result in costly and time consuming changes to missile, radar, or launcher design.

Finally, organizational and funding issues have hampered the establishment and efficiency of engineering change control and integration management. These are critical efforts to support integration of the JUWL-equipped missiles with the new combat system, radar, and launcher. Delays in these processes make an already challenging development effort that much more difficult.

The thesis recommends that DOD acquisitions continue to emphasize and enable rigorous application of system engineering principles early in the acquisitions process; that all programs perform a thorough flow-down of requirements even if utilizing legacy systems; and that all funding for weapon development be placed in the control of the Program Executive Office for Integrated Warfare Systems. All of these recommendations are based upon results from prior development efforts as well as systems engineering standards and best practices from academia, industry, and government. In particular, the critical importance of integration is supported by Langford's *Engineering Systems Integration: Theory, Metrics and Methods* and Krygiel's *Behind the Wizard's Curtain: An Integration Environment for a System of Systems* (Langford 2012; Krygiel 1999).

Finally, the thesis contends that consolidation of resources and control over systems engineering processes is supported by the historical success of the Aegis combat system and the Navy nuclear power program. Both efforts were afforded complete control over all aspects of their respective system designs, improvements, training, maintenance, and support.

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I. INTRODUCTION

A. BACKGROUND

The Department of Defense (DOD) has found it increasingly difficult to develop and acquire advanced systems for military use that meet cost, schedule, and performance goals (Kadish 2005; Charette 2008). The problem will be even more challenging in the foreseeable future as defense budget levels are expected to remain stagnant for the next decade (Congressional Budget Office [CBO] 2013).

The DOD has had a long struggle with efficient system development and both identified causes and potential solutions have been proposed for as long as the DOD has existed (Kadish 2005). The systems acquired are often based on extremely advanced technology, have extremely high performance standards, and are expected to operate in harsh environments. They are expected to have long service lives and to be very reliable, easy to maintain, and easy to repair. Systems are also increasingly expected to be interoperable with other new and legacy systems as the DOD continues to pursue its “net-centric” paradigm for weapons systems (Defense Acquisition University [DAU] 2010). All of these desired factors, but particularly the drive for ever-increasing performance, would naturally be expected to increase the anticipated cost and development time for the system.

However, there is also an expectation of “affordability” for every system (Welby 2013). Congress has cut or significantly curtailed programs that have extremely high per-unit cost compared to previous versions of similar systems, despite improved performance. For instance, final numbers of the B-2 “Stealth” bomber, the Seawolf class submarine, and the F-22 fighter programs were dramatically reduced after it became apparent that each would have an extremely high per-unit cost. There are certainly other factors that influenced Congressional decision-making on these programs, including perceived threats, schedule delays, and so forth, but cost is one of the primary lenses through which Congress examines programs (Rand Corporation 2011a).

One of the methods the DOD uses to attempt to save money in acquisition is the re-use of existing systems, sub-systems and components. The Zumwalt-class ship program, also known as the Guided Missile Destroyer-1000 or DDG-1000 program, was directed to use existing missiles in its design, thus sparing the expense of developing an all-new missile. This directive was believed to require minimal effort as the missiles would only need to be modified to operate with the new radar featured on DDG-1000. Therefore, integration activities and associated funding have been very limited in comparison to "new development" programs. Furthermore, the modification effort was not organized according to traditional development program guidelines but was instead pursued through a contractual modification to an existing engineering support contract. DDG-1000 is currently scheduled to begin operational test and evaluation (OT&E) activities in 2015 (O'Rourke 2013).

B. PURPOSE

The purpose of this paper is to examine the history of combat systems development in the DDG-1000 program, specifically the integration of legacy missiles with the new-development radars and combat system of DDG-1000, in order to evaluate the validity of published "best practices" as well as identify new lessons learned that can be utilized by future acquisition programs.

C. RESEARCH QUESTIONS

No DDG-1000 ships have been launched and no missiles have been fired from the ship. Therefore, it is problematic to discuss missile integration efforts in absolute terms of "success" or "failure." However, the history of the DDG-1000 program and the missile integration effort in particular are long enough to allow them to be examined in relation to established government, industry, and academic standards. This thesis will address the following questions: What lessons can be learned from the integration of legacy missiles with the new-development combat systems of DDG-1000? Does missile integration on DDG-1000 validate or reject integration "best practices" as described in government policy documents, industry standards, and articles in scholarly journals?

D. BENEFITS

It is hoped that the case study presented in this thesis will provide readers with a relevant analysis of "what works" when integrating legacy weapons systems into a new, complex platform.

E. SCOPE AND METHODOLOGY

This paper will address the integration of legacy missiles into the new-development combat systems of DDG-1000 via analysis following a literature review. The paper will address technical and programmatic decisions from the inception of the DDG-1000 program until now, and will identify potential future risks based on the historical analysis. Sources for the literature review include program artifacts such as acquisition milestone reviews, briefings, and risk assessments; government reports including Congressional testimony and Government Accountability Office documents; scholarly articles, textbooks, and theses on the topics of acquisition and integration; defense, acquisitions, and systems engineering professional journals; and DOD acquisition, engineering, and program management guidance documents.

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II. HISTORY OF THE DDG-1000 PROGRAM

A. INTRODUCTION

The DDG-1000 has been one of the Navy's most visible and controversial development projects for almost twenty years. This chapter will describe the strategic and operational context in which the program was initiated. It will describe the key operational and technical features of DDG-1000 and will highlight key events since the program's start. This chapter will also describe the current state and potential future for DDG-1000, which is far different from its original announced purpose.

B. GENESIS OF THE PROGRAM

The DDG-1000 program began in 1994 (Hagerty et al. 2008). It was an outgrowth of the "Surface Combatant for the 21st Century (SC-21)" study the Navy conducted in the early 1990s (O'Rourke 2013). Originally known as DD-21, and then DD(X), it was planned as a significant class of 32 warships. It was part of a family of three future warship classes conceptualized to implement the Navy's post-Cold War strategic vision. The three proposed ship classes were the DD(X), the CG(X), and the LCS. The new strategic vision, outlined in the Navy document *Forward…From the Sea*, reflected a change in emphasis from open ocean dominance against a peer adversary to power projection and influencing events ashore (Dalton 1994). The three ship classes reflected that shift. The DD(X) would provide precision strike against land targets, the CG(X) would provide advanced air and ballistic missile defense, and the LCS would provide surface and antisubmarine (ASW) capability in the littorals (CBO 2003). The Navy originally intended the new ship to replace the FFG-7 and eventually the DDG-51 class ships, at a per-unit cost less than that of the DDG-51 (Hagerty et al. 2008).

The new strategy was based on the perceived lack of a near-peer adversary capable of challenging U.S. dominance on the open ocean. It also reflected a new belief that the technological dominance of U.S. forces (demonstrated during the First Gulf War) would allow the U.S. to fundamentally alter the nature of warfare. This "Revolution in Military Affairs" (RMA) paradigm dominated strategic thinking in the early to mid-

1990s and spurred a military acquisition philosophy that emphasized acquiring even more advanced technologies (Metz and Kievit 1995). During the 2000 presidential campaign, then-candidate George Bush gave speeches calling for the Pentagon to "skip a generation of weapons" in order to achieve overwhelming dominance against any potential adversary (Owens 2013).

The 1993 Defense Bottom-Up Review (BUR; forerunner of the Quadrennial Defense Review) was explicit in describing how the U.S. would apply this technological superiority to defeating two simultaneous enemies in regional wars (Aspin 1993). The Middle East and Korean peninsula were specifically cited as potential hotspots, and significant discussion was given to potential "dangers to democracy and reform" in the former Soviet Union and Eastern Bloc (Aspin 1993, 2).

These new systems would be combined into a "net-centric" architecture. This architecture, supported by equally advanced command and control systems, would give U.S. forces an overwhelming advantage against regional adversaries. The Navy "vision statement" *SeaPower 21* described this architecture in naval terms (Clark 2002). While the RMA may have fallen from the front page of the strategic debate, it continues to shape military acquisition. Every major new weapon system is described in terms of its "net-centric" capabilities and its ability to operate in a joint environment (DAU 2011).

DDG-1000 reflected the "generation after next" technology sought by the Navy and the RMA. The ships would feature advanced land attack capabilities, allowing them to take the place of the recently retired Iowa-class battleships. The ships would not only launch Tomahawk missiles but were also to feature an advanced gun system firing extended range projectiles to perform naval surface fire support (NSFS) missions. They would also have low-observable characteristics facilitating their operation in littoral areas. They were to feature a host of other technological improvements allowing for expansion of capabilities as even newer technologies became available. For instance, the ship's integrated power system was envisioned as powering lasers, rail guns, or other emerging technologies. Finally, the ships were to utilize the "reduced manning" concept, automating previously manpower-intensive functions and thus costing less to operate than traditional warships (Liszniansky 2006).

There were a total of ten critical technologies (see Figure 1.) identified in the DDG-1000 program (Government Accountability Office 2004):

- Wave-piercing tumblehome hull design
- Advanced Gun System (AGS) and Long-Range Land Attack Projectile (LRLAP)
- Integrated Composite Deckhouse and Apertures
- Total Ship Computing Environment (TSCE)
- Dual Band Radar (DBR)
- Integrated Undersea Warfare System (IUWS)
- Peripheral Vertical Launch System (PVLS)
- MK 57 Vertical Launch System (VLS)
- Automatic Fire Suppression System (AFSS)
- Integrated Power System (IPS)

Figure 1. DDG-1000 Critical Technologies (from Liszniansky 2006)

This ambitious level of technological development in a single hull was precisely what was called for by the Navy's strategic vision. However, it ran counter to established Navy shipbuilding policy that limited technological advances to two or three areas in a new ship design. The great success of the DDG-51 class can be attributed, at least in part, to the fact that it re-used almost every significant ship system featured on the CG-47 class cruiser. Re-use of those successful systems greatly lowered the technological risk of the program (Hagerty et al. 2008).

C. EVOLUTION OF THE PROGRAM

The program began in earnest in August of 1998 as the Pentagon awarded contracts to two different industry groups to begin work on system concept designs (Defense Industry Daily 2013). Work was performed throughout 1999, 2000, and 2001. The original acquisition plan included a "winner take all" decision to select a design submitted from two industry teams, headed by Bath Iron Works and Ingalls Shipbuilding. This unique approach had never been applied to a major shipbuilding program before (Office of the Assistant Secretary of Defense 2002).

New threats began altering national priorities during the period of initial design work. Even before the terrorist attacks of September 11th, 2001, the Pentagon and new administration had been working to define a new strategic vision and a more flexible, adaptable military. The 2001 Quadrennial Defense Review (QDR) emphasized ballistic missile defense, threats from failed states and non-state actors, and the need to transform U.S. forces to defeat such "asymmetric" threats (Office of the Secretary of Defense (OSD) 2001). The RMA transformation was now presented as the way to defeat such asymmetric threats. The terrorist attacks of September 11th and the resulting occupation of Afghanistan and Iraq marked a return to low intensity and counter-insurgency warfare. These experiences seemed to validate the QDR's emphasis on flexibility; this type of conflict was a far cry from the technologically driven force-on-force "Sea Strike" that had been anticipated in *SeaPower 21*. The need for a conventional surface vessel armed with lasers or rail guns seemed far down the list of priorities. By December of 2001, DD-

21 was officially cancelled. The reasons cited included rising cost estimates and lagging technological development (O'Rourke 2004).

The DD-21 was immediately replaced with DD(X) (Defense Industry Daily (DID) 2013). In April of 2002, Ingalls (now part of Northrop Grumman Ship Systems) won the "winner take all" design decision and was awarded a $2.8 billion contract for detailed design of their winning proposal (DID 2013).

The Navy remained a strong proponent of the program, continuing to cite the need for the new destroyer. The procurement was reduced to 24 ships, however, at which time the planned CG(X) vessels would be ready for construction. Both Navy and CBO cost estimates continued to rise as technology development lagged behind schedule (Hagerty et al. 2008).

By the time the Navy revised its 30-year shipbuilding plan and presented it to Congress in 2005, DD(X) had been reduced to "8–12" ships (Hagerty et al. 2008, 15). This was driven by the ever-increasing cost estimates for the ships, which in turn were driven by slow technological development. The CBO estimated that the lead ship would cost $3.3 billion and have life cycle costs nearly double that of the DDG-51 class (DID 2013). Ironically, 2005 saw many of the critical technologies pass significant testing and readiness milestones, including the Total Ship Computing Environment (TSCE), the Dual Band Radar (DBR), the hull form, and the Peripheral Vertical Launch System (PVLS). The ship also passed its initial flag-level Critical Design Review (CDR) in September of 2005. The perception of yet another over budget and behind schedule program was firmly entrenched in Congress, however, and scrutiny of the program continued.

In April of 2006, the Navy announced a new plan for procuring seven DDG-1000 ships and the FY2007 budget authorized construction of the first two vessels (O'Rourke 2008). The Navy had also continued to alter its fundamental strategic vision to include homeland defense, cooperation with international partners, and provision of humanitarian assistance (Roughead 2007). The specific mention of homeland defense signified the increasing importance of sea-based ballistic missile defense. And although the *Cooperative Strategy for 21st Century Seapower* retained the concepts of forward presence and dominance in regional war, the new emphasis on engagement and "low-level" operations continued to widen the gulf between the new, large and expensive DDG-1000 and the Navy's self-professed needs. The evolving vision was much more in line with the second of the three SC-21 vessels, the Littoral Combat Ship (LCS) (a program which has had its own share of problems). DDG-1000 was also out of consideration for performing the existing BMD mission (which fell to BMD-capable *Aegis* platforms) and the future BMD mission (which were to be fulfilled by CG(X)).

The Navy's justification for continuing the DDG-1000 stated that it would serve as a technological bridge to CG(X). The Navy also claimed that DDG-1000 would not only be able to perform its original mission of littoral fire support but that it was also fully capable of conducting the blue water, fleet support missions of the DDG-51. This line of reasoning may have backfired as the argument opened the DDG-1000 up for direct comparison directly to the DDG-51 in terms of cost, performance, sea-keeping, and a host of other factors. The appropriateness of such a comparison continues to be a source of debate (Miller 2012).

Cost estimates and criticism on Capitol Hill continued to rise in 2007 and 2008. Navy estimates at per ship cost had risen to $3.3 billion each and some outside sources estimated $5 billion or more (Hagerty et al. 2008). Even with the most optimistic estimates, DDG-1000 was shaping up to be the most expensive non-nuclear surface vessel the Navy had ever bought. Skepticism concerning some of the ten critical technologies also became pronounced, including serious discussion about the stability of the new hull design and the capability of the ship to perform area air defense and open-ocean ASW (DID 2013). In 2007 and 2008, Congress began openly challenging the Navy's shipbuilding plans and there were repeated calls to restart DDG-51 production, which had ended in 2005 (DID 2013).

In July of 2008, Chief of Naval Operations (CNO) Gary Roughead testified before Congress that the Navy wanted to limit production of DDG-1000 to just two ships and re-start the DDG-51 production line in order to meet its future surface combatant needs (Hagerty et al. 2008). This plan also entailed cancellation of the CG(X) program. The first five re-started DDG-51 hulls would be Flight IIA types; production would then shift to a Flight III design which would be developed to meet the BMD mission. This complete reversal in policy was a shocking turnaround given how strongly Navy leadership had defended the program in the past. The reasons for this change were numerous but are perhaps best captured in these two statements by the CNO:

> While there are cost savings associated with the DDG 1000′s smaller crew, they are largely offset by higher estimated maintenance costs for this significantly more complex ship. Clearly the relative value of the DDG 1000 resides in the combat system (Dual-Band Radar, Volume Search Radar, ASW Suite, etc.) that provide this ship with superior warfighting capability in the littoral. However, the DDG 51 can provide Ballistic Missile Defense capability against short and medium range ballistic missiles and area Anti-Air Warfare capability (required in an anti-access environment) where the DDG 1000 currently does not. Upgrading the DDG 1000 combat system with this capability would incur additional cost. The DDG 51 class also possesses better capability in active open ocean anti-Submarine Warfare than does the DDG 1000. On balance, the procurement cost of a single DDG 51 is significantly less than that of a DDG 1000, and the life-cycle costs of the two classes are similar. (Roughead, quoted in DID 2013)

> I started looking at the DDG-1000. It has a lot of technology, but it cannot perform broader, integrated air and missile defense… Submarines can get very close [due to design compromises], and it does not have the ability to take on that threat… And I look at the world and I see proliferation of missiles, I see proliferation of submarines. And that is what we have to deal with. (Roughead, quoted in DID 2013)

A third DDG-1000 was eventually authorized in the FY2009 Defense Budget Authorization, although the Navy was given the ability to transfer the funding ($2.5 billion) to DDG-51 construction if it chose to do so. The third DDG-1000 was primarily a Congressional move to support the shipyards in Bath, Maine, and Pascagoula, Mississippi.

The decision to end the DDG-1000 program after three ships obviously had significant consequences. First, the decision resulted in a Nunn-McCurdy breach for the program, formally reported to Congress in April 2010. The Nunn-McCurdy provisions were first included in the 1982 Defense Budget Authorization Act and were subsequently enacted into the U.S. code (Rand Corporation 2011). They call for any defense acquisition program to be reviewed or presumptively cancelled if the program exceeds cost estimates by certain percentages. In order to avoid the presumptive cancellation, the acquisition authority for the program must provide certification of certain criteria for the program to Congress. These criteria include:

- The program is essential for national security
- No alternatives will provide an acceptable capability to meet requirements and that new estimated of PAUC and APUC have been determined to be reasonable by CAPE
- The program has a higher priority than the programs whose funding must be reduced to accommodate the "breaching" program
- The management structure of the program is adequate to manage and control PAUC or APUC (Rand Corporation 2011, 20)

The provisions examine two basic measures of program cost. PAUC is the total development and procurement cost divided by the number of items procured. APUC is the total procurement cost divided by the number of items procured. The triggers associated with Nunn-McCurdy are summarized in Table 1. :

Table 1. Nunn-McCurdy Provisions (from Rand Corporation 2011, 15)

Breach Type	*Measure examined*	*Baseline*	*Trigger Level*
Significant	PAUC	Current	≥ 15%
	APUC	Current	≥ 15%
	PAUC	Original	≥ 30%
	APUC	Original	≥ 30%
Critical	PAUC	Current	≥ 25%
	APUC	Current	≥ 25%
	PAUC	Original	≥ 50%
	APUC	Original	≥ 50%

The reduced quantity of ships resulted in a new PAUC of $5.8 billion, up from $3.1 billion that had been estimated at the 2005 program baseline. A root cause analysis was completed by the Office of the Secretary of Defense's (OSD) Performance

Assessments & Root Cause Analysis (PARCA) office to determine reasons for the overrun. The main driver was, as expected, the reduction in quantity of ships. PAUC and APUC are very sensitive to quantity fluctuations. However, PARCA also identified other factors contributing to DDG-1000's enormous cost growth. The results are summarized in Table 2. :

Table 2. DDG-1000 Cost Growth Root Causes (from Rand Corporation 2011, 25)

Acquisition phase/activity	*Cost growth root cause*
Baseline determination	Unrealistic estimate
	Immature technology; excessive manufacturing and integration risk
	Unrealistic performance expectations
Program execution	Changes in procurement quantity
	Funding instability
	Unanticipated technical issues

The PARCA analysis, much like a 2009 GAO report, highlighted continuing concerns about technology maturity on some of the ship's critical systems. It warned that since the first hull had just begin construction, and many of the technologies would not be certified until after installation, the program was accepting a high risk of potential re-work or even design changes. In particular, the GAO cited the TSCE and the VSR radar as "immature" and several years behind schedule (GAO 2009).

In June of 2010, the Navy announced that the VSR portion of the DBR would be removed from the ship design (DID 2013). The removal of VSR was a cost/benefit decision, saving approximately $100 million for each hull. It also required modifications to the MFR radar, allowing it to perform some search functions. The decision was also influenced by the development of the AMDR, the next generation ballistic missile defense radar which was intended for the future Flight III DDG-51 (Miller 2012). Rising costs and limited space on the DDG-51 hull for the new AMDR meant that "retro-fitting"

AMDR into the DDG-1000, as well as the possibility of increasing the DDG-1000 procurement and modifying it into the next generation of BMD ship (instead of building DDG-51 Flight III), became real possibilities. These issues will be discussed in greater detail in Chapter III on combat systems development.

Finally, the Navy recently began investigating the potential of using regular steel, instead of advanced composites, to construct the deckhouse for DDG-1002 (Fabey 2013). This is another cost saving move which the Navy claims will not affect the "stealth" characteristics of the ship. The composite materials have been a challenge for both shipyards involved in DDG-1000 construction.

D. CURRENT STATUS

The DDG-1000 program is no longer the centerpiece of the future Navy. The original procurement of 32 ships has been reduced to just three. A program once touted as the future of the Navy is now essentially advertised as a test-bed for technologies that will be installed on other combatants (Miller 2012). Costs, as predicted by various agencies since the start of the program, have greatly exceeded estimates and are summarized in Table 3. :

Table 3. DDG-1000 Cost Growth Summary (from GAO 2013, 55)

Measure	*1998 Baseline*	*Aug 2012*	*% change*
Total ships	32	3	- 90%
Total cost	$34.8	$21.5	- 38%
Research & Development Cost	$2.3	$10.3	+ 353%
Procurement Cost	$32.5	$11.1	- 65%
Per ship cost: APUC	$1.0	$7.2	+ 543%
PAUC (without R&D)	$1.0	$3.7	+ 248%
Total acquisition time (in months)	128	222	+ 73%
all $ in billions			

As of March 2013, DDG-1000's hull is approximately 82% complete. DDG-1001 is approximately 52% complete, and DDG-1002 has begun (Zumwalt Program Office 2013). Most of the critical technologies will not have been demonstrated until after their installation in the hull, a point of technical risk that has been raised since 2004 (GAO 2013). The program is placing a great deal of faith in its Engineering Development Model (EDM) risk mitigation strategy. The strategy calls for EDMs to be built and tested for all critical technologies so that significant issues can be discovered earlier in the design and development phase of the program. DDG-1000 is scheduled to be delivered to the Navy in 2014 with a significant OT&E period to follow.

In considering the program as a whole, one can only conclude that the Navy has yet to learn the lessons of previous major acquisition programs. When per unit costs become excessive, Congress will simply balk at the expense, regardless of technological advances. The desire for technological advancement inevitably leads to schedule delays, which in turn means that the strategic and operational needs of the service may have changed in the interim. This affected DDG-1000 particularly hard, as the concept of a land-attack ship was new to the Navy anyway.

The DDG-1000 now enters the same territory as the B-2 bomber, the F-22 fighter, and the Seawolf submarine: a platform with potentially enormous capabilities that the nation has decided is too expensive to build and operate. While acknowledging the fact that rising DDG-51 Flight III costs may still allow the DDG-1000 to re-enter the conversation as a possible future BMD platform, the ship's main legacy will likely hinge upon how many of her transformational technologies become mainstays for other ships.

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III. DDG-1000 COMBAT SYSTEM DEVELOPMENT HISTORY

A. INTRODUCTION

One of the hallmarks of the DDG-1000 program has been the stated intent to develop and field the most cutting-edge technologies possible for naval warfare. Advanced technologies were to be implemented in every area of the ship, from the material used to build the deckhouse to the method of providing main propulsion. There were a total of ten critical technologies identified in the program (GAO 2013). Combat systems advancements were the leading features of the program, but challenges in developing these technologies have given rise to criticism of DDG-1000 for both effectiveness and cost-effectiveness (Miller 2012). This chapter will briefly outline the history of combat systems in the program. Primary attention will be given to the DBR because it is the primary item that must integrate with missiles, although the launcher will also be examined.

B. THE ADVANCED GUN SYSTEM AND LONG-RANGE LAND ATTACK PROJECTILE

In one sense, the Advanced Gun System (AGS) and Long-Range Land Attack Projectile (LRLAP) are the *raison d' etre* for the entire DDG-1000 program. As described in Chapter II, precision land attack and Naval Surface Fire Support (NSFS) are the primary mission of the class. The advent of the Tomahawk cruise missile had made the surface Navy relevant again for strategic and pre-emptive strikes against enemy targets. However, the final retirement of the Iowa-class battleships in the mid-1990s meant that the Navy's traditional role of providing tactical fire support to troops ashore was limited to the 5-inch guns of the DD-963, CG-47 and DDG-51 classes. Many in Navy and Marine circles felt the weapons were simply inadequate for the task, having limited range and firepower (Welch 2007).

However, even with the relative deficiencies of current 5-inch guns compared to the Navy's retired 8- and 16-inch guns, the benefits of naval gunfire for the NSFS mission are still pronounced. Ships can provide a constant volume of firepower in contrast to air-delivered support (which has a cycle time). Gunfire is also vastly less expensive per shot than a cruise missile or air-delivered ordnance.

The AGS system was intended to overcome the deficiencies of the Navy’s 5-inch gun system. It is a 6.1-inch (155mm) gun system with a fully-automated ammunition handling and loading system. It will meet extended range requirements by utilizing the rocket-assisted and precision-guided LRLAP round. It will also be capable of firing conventional (unguided) 155mm rounds (DID 2013). The weapon’s magazines will hold approximately 600 rounds (O’Rourke 2013).

Technical risks and delays with the system have revolved primarily around the rounds themselves. The Extended Range Guided Munition (ERGM) program was a twelve-year, $600 million failed effort to develop an extended range round to be fired from the existing 5-inch/54 gun system (Matthews 2008). The primary challenge is developing internal guidance components that can withstand the shock of being fired from an artillery piece. LRLAP also had to redesign its rocket booster, although earlier tests had met range requirements. The program had a successful flight test of its redesigned round in early 2013 and contracts are now in place to install AGS in all three DDG-1000 hulls (DID 2013). Concerns about limited magazine capacities on the ships remain, but the AGS and LRLAP are expected to meet the requirements set for them. Whether or not those requirements meet the needs of the Navy will not be known until the ship is employed.

C. MK57 VERTICAL LAUNCHER SYSTEM AND PERIPHERAL VERTICAL LAUNCH SYSTEM

DDG-1000 features two improvements in missile launcher design when compared to the current mainstay of the Navy: the MK41 vertical launcher system (VLS) installed on the CG-47 and DDG-51 classes (and multiple allied ship classes).

The first improvement is the MK57 launcher itself. The launcher’s cells are larger than the MK41, allowing it to carry all current VLS weapons and accommodate future weapons that could feature increases in length, weight, and diameter. It features an open architecture design, which should minimize the amount of modification required to accommodate those future weapons. In particular, the canister electronic unit (CEU) will serve as an interchangeable interface between weapon and launcher, eliminating the need to otherwise permanently modify launcher hardware or software to accept a particular weapon. Thus, the system should meet the Navy's desired "any missile, any cell" design (Raytheon 2013). The ship's combat system would still need to be modified to ensure that it could communicate with the new weapon via the CEU. These modifications are presumed to be software adjustments only. Finally, the launcher's gas management system is also designed to accommodate future weapons and their expected increases in rocket motor exhaust mass and flow rate (Raytheon 2013).

The second innovation on DDG-1000 is the introduction of the peripheral vertical launch system (PVLS). Although sometimes confused in the literature with the Mk57 launcher itself, the PVLS denotes the arrangement of the MK57s throughout DDG-1000's hull and their protection by a new armored enclosure (DID 2013). There are 20 groups of four missile cells each distributed outboard on the hull. The armored enclosures are designed to funnel explosive energy out and away from the ship's hull during combat, thus protecting the internal spaces of the ship as well as adjacent launcher cells. The current Mk41 VLS is a single "bloc" of cells, centerline on the CG-47 and DDG-51. A single hit on the Mk41 in combat could cause the entire launcher to be inoperable, thus depriving the ship of its primary AAW armament.

Like almost all new technologies on the DDG-1000, the Mk57/PVLS encountered some technical challenges and schedule delays. The new launcher has not, however, been a significant programmatic or technical risk to date (DID 2013).

D. DUAL BAND RADAR

1. Brief Description of Current Radars

Before describing the development of the DBR for DDG-1000, it may be helpful to briefly review the operation of a typical microwave radar and highlight the characteristics of radar systems that use conventional antennas and those using phased arrays.

Figure 2. shows a generic microwave radar and its main components.

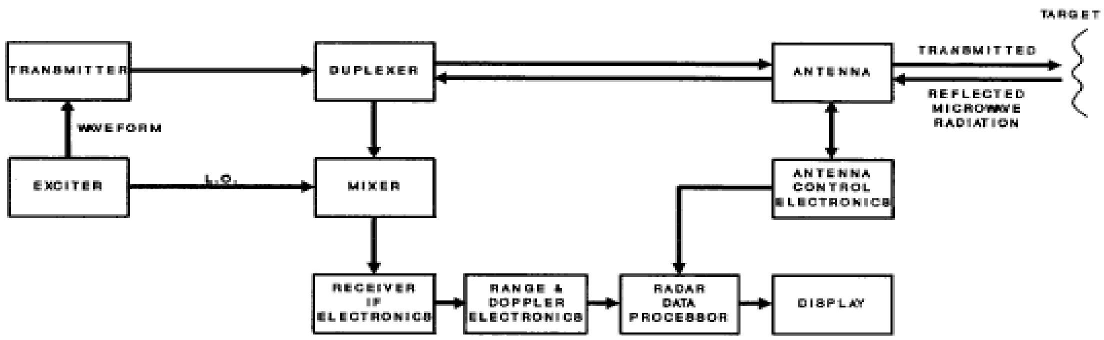

Figure 2. Generic microwave radar (from Harney 2005, 87)

In the most general sense, a radar system generates electromagnetic radiation and transmits it into the atmosphere. The radiation scatters when encountering objects; the scattered signal that returns to the radar antenna can be evaluated to determine the bearing and range to the object. Repeated transmissions and returns can be analyzed to extrapolate the object's speed and direction of travel (Naval Education and Training Command (NETC) 2000).

All radars use some form of antenna to focus the transmitted signal in a certain direction of travel and into a certain beam form. It is by using this directionality and focus as a reference point (as well as known constants for signal speed) that the radar system assesses the returned signal to give useful information to the radar operator. A "traditional" microwave radar uses some form of a parabolic dish to focus the transmitted energy of the radar (see Figure 3. for common types). This dish is mechanically moved through the desired field of regard by a series of motors and gimbals. For instance, an air-search radar will typically spin 360 degrees to search the most volume of air space possible around the radar set itself. A monostatic radar uses the same antenna to transmit and receive the RF energy. A duplexer controls the timing and channeling of the sent and received signals so that there is no interference internal to the system. A bistatic radar uses a separate dish for sent and received signals. The two antennas are usually in close physical proximity to each other (Harney 2005).

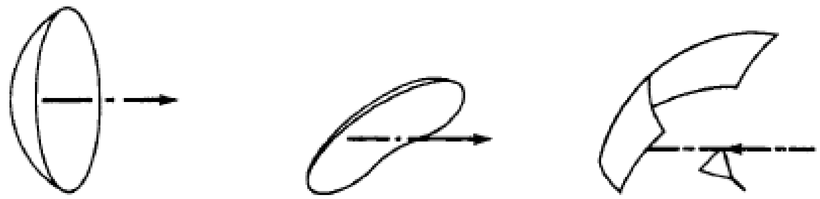

Figure 3. Common Reflective Antenna Shapes (from Skolnick 2008, 560)

Variations in the characteristics of the radar (frequency/wavelength, amount of power generated by the radar, rate of antenna spin, etc.) result in performance differences. Those performance differences are maximized depending on the intended function of the radar. As mentioned, air search radars typically cover a 360 field and are designed to transmit energy into the widest area possible. They can have detection ranges in excess of 200 nautical miles (NETC 2000). A missile director, on the other hand, typically features a very narrow beam that is steered only the amount necessary to keep its target within the director's beam.

In the naval environment, radars have been optimized for surface detection and tracking, gunfire support, air search and tracking, missile guidance, and so on (NETC 2000). Search and track radars are typically "pulsed" beam forms, meaning that the RF energy is emitted in pulses. During the non-transmitting period of time the radar receives and processes the return from the target. The more rapidly the radar "pulses" its signal the more rapidly it can update its target information. However, high pulse repetition rates (PRR) reduce the effective range of the radar. Illumination radars are often have extremely high PRR or are of the continuous wave type because intercepting a fast target requires the most accurate target position possible. Continuous wave illuminators utilize the frequency shift between its own signal and the target return signal (the Doppler shift) to determine target range, etc. They are often of the bistatic type–the NATO SeaSparrow missile system is a good example (NETC 2000).

It is important to note that missile engagement systems that utilize continuous wave illumination require the missile to have a receiver onboard the missile to receive the reflected energy from the target, a processor to calculate target position in relation to the missile's own position, and an autopilot which will command the missile to maneuver to intercept the target. The illuminator uses the reflected energy to calculate a pointing position to maintain its beam on the target (NETC 2000). When used in an environment where targets are travelling at high subsonic or supersonic speeds and have a small radar cross-section, it becomes clear that these calculations and updates must be performed as rapidly as possible.

While traditional antenna systems are a very capable and mature technology, they do have significant drawbacks. First, the mechanical systems required to allow the RF energy to be coupled into the moving antenna are complex and prone to failure (or are, at least, maintenance-intensive). Second, the varying characteristics needed for different applications are implemented primarily via the physical and mechanical characteristics of the radar; which meant that ships needed a multitude of independent radar systems to accomplish their varying missions. As mentioned, the frequency and pulse width of the radar, which greatly determine its range resolution, are fixed by its electronic and mechanical properties, as are its maximum effective range, performance against certain size targets, and so on (O'Donnell 2010; NETC 2000).

Consider the DD-963 class destroyers, which entered the fleet in the mid-1970s. By the early 2000s, the ships had a wide variety of radar systems installed as listed in Table 4. .

Table 4. DD-963 class installed radars

Radar	*Function*
SPS-40	Air search
SPS-55	Surface search
SPS-64	Surface search
Furuno	Commercial surface search radar, used for navigation support
SPG-60	Air target fire control for MK86 gunfire control system (5" guns)
SPQ-9	Surface target for control for MK86 gunfire control system (5" guns)
MK23 TAS (Target Acquisition System)	Air search radar for the SeaSparrow weapon system
MK95	Fire control director for SeaSparrow weapon system
MK15 Phalanx	Two radars (search and track) to support the MK15 Phalanx CIWS (Close In Weapon System)

Each of these systems requires maintenance and upkeep, specific training for both operation and maintenance, spare part support (which entails a logistic support system), and so on. The complexity of the systems removes the possibility of cross-training sailors to operate and maintain more than one system; indeed the Navy has multiple ratings of sailors to perform those functions.

A phased-array radar introduces a new approach to implementing radar antenna functionality. The antenna is a flat panel of multiple emitting elements. The radar signal can be adjusted (via phase timing) so that each module emits its signal to produce a coherent radar beam in a desired direction (as seen in Figure 4.). This greatly improves performance. It increases the speed with which the radar can scan its field of view and it eliminates the complex mechanical systems required for a moving antenna (NETC 2000).

The time required for a mechanically-scanned radar to move its field of view 20 degrees is measured in seconds. A phased array can perform the same re-direction in microseconds (O'Donnell 2010). This enormous improvement, coupled with the power of modern computers to process returned signals, results in dramatic performance improvements. The radar can produce extremely accurate information about the contacts it is tracking. Recall the earlier discussion of the necessity of accurate information when attempting to accurately track and intercept high speed targets.

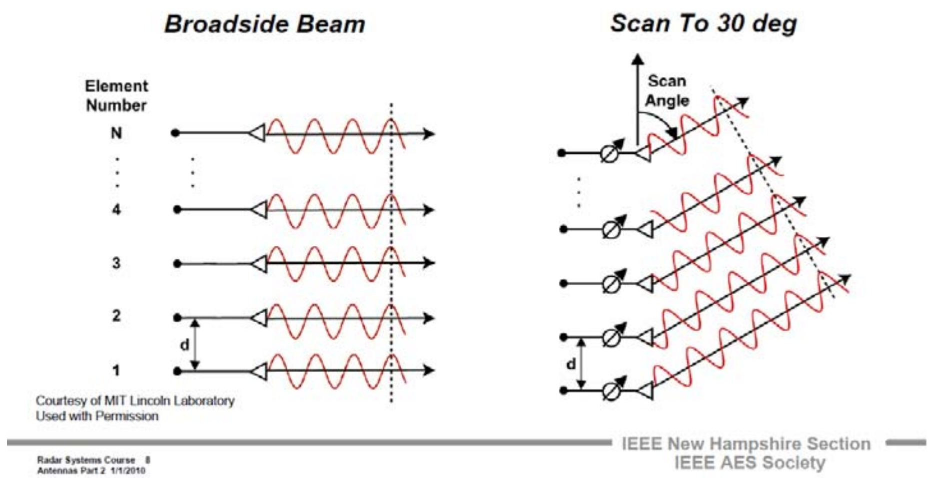

Figure 4. Formation of radar wave by phased array (from O'Donnell 2010, 8)

The phased antenna also allows the radar to form multiple beams by selectively controlling the timing and phase of the elements, which in turn allows the radar to perform multiple functions simultaneously as shown in Figure 5. (O'Donnell 2010). All phased array antennas with a sufficient number of elements can perform multiple functions if the control software allows it; one must be cautious in interpreting the names and nomenclature of specific radar systems. For instance, the SPY-3 radar destined for DDG-1000 is commonly known as the Multi-Function Radar (MFR). Likewise Thales advertises its APAR as the first "true" multi-function radar despite Aegis' operational history since 1983 (Thales 2013, Jane's 2013).

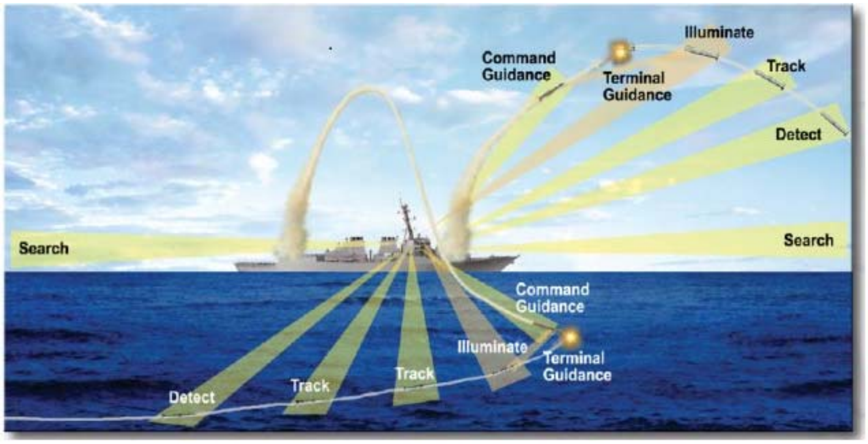

Figure 5. SPY-1 Functions (from Lockheed Martin 2013)

Because of limits on the amount of phase shift that can be applied to the emitted RF energy in a phased array, such systems typically feature three or four arrays spaced to ensure 360 degree coverage (White and Billups 2008). Other variations include a single array that is mechanically moved, creating a hybrid mechanical/phased antenna (Skolnick 2008).

Phased array radars are commonly referred to as either “active” or “passive.” The distinction lies primarily in how power is generated in the radar. “Passive” denotes that the individual modules in the antenna array receive their power from a common source as is the case in a traditional antenna setup (see Figure 6.). This requires extensive “plumbing” to support the creation of the signal, transmission to the elements, and environmental controls for the entire arrangement. The space required for the hardware and its associated weight is one of the main considerations for shipboard implementation of this type of radar (Harney 2005). In particular, the necessity for extensive waveguide hardware results in loss of signal strength and potential for mechanical failure (Al-Rashid 2009). This is not to say that traditional radars did not require extensive apparatus to operate; it is merely to point out that no improvement is without its limitations. As an example, the sea-based X-band radar (SBX) developed for the Missile Defense Agency (MDA) utilized a phased array antenna. The radar and its ancillary equipment are installed on a modified offshore oil drilling platform that is over 280 feet tall (Goldberg 2006). The entire system weighs over 4 million pounds (Skolnick 2008). The ongoing debate about the suitability of the DDG-1000 or the DDG-51 Flight III as a suitable host for the AMDR depends greatly upon the capacity of the hull to accommodate the radar and its ancillary equipment (O'Rourke 2012).

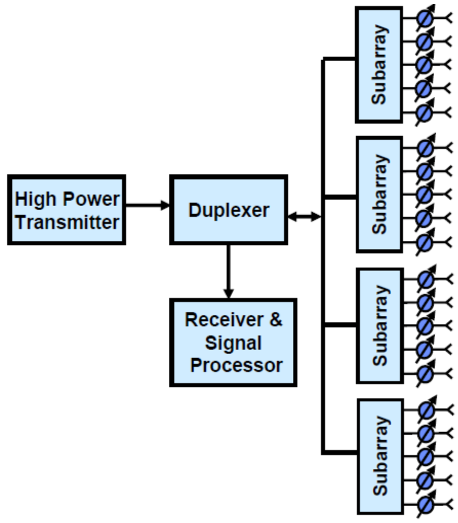

Figure 6. Typical Passive Array Arrangement (from O'Donnell 2010, 50)

SPY-1 is an S-band passive phased array radar (NETC 2000). The SPY-1 has 4,350 elements per antenna array. The elements are subdivided in 32 "modules" or "subarrays" for transmission and 68 for receipt. This facilitates the division of power in the array (Jenn 2013). Aegis ships have four arrays positioned to provide 360 degree coverage. The Aegis system is far more than just the radar information processor–it is the heart of a multi-mission warfare command system (see Figure 7.). In addition to the SPY-1 radar, the ships utilize the SPG-62 fire control radars for terminal phase illumination of targets. The Aegis system processes the incoming radar information and allocates radar resources to continue conducting search, track, and missile uplink functions. It also transmits the target information to the missiles it launches and "cues" the SPG-62 radars to provide the required terminal phase illumination (Jane's 2013). As seen in the diagram, the Aegis system utilizes other sensors beside the SPY-1; these can include other air and surface search radars. Use of these sensors provides two main benefits. First, the additional sensors may be optimized for performance in a certain area (for example, the SPS-49 is an extremely long-range air search radar) that can augment

SPY-1's capabilities. Second, the additional sensors provide redundancy and provide the combat system decision system with additional resources to identify, evaluate, and process contacts.

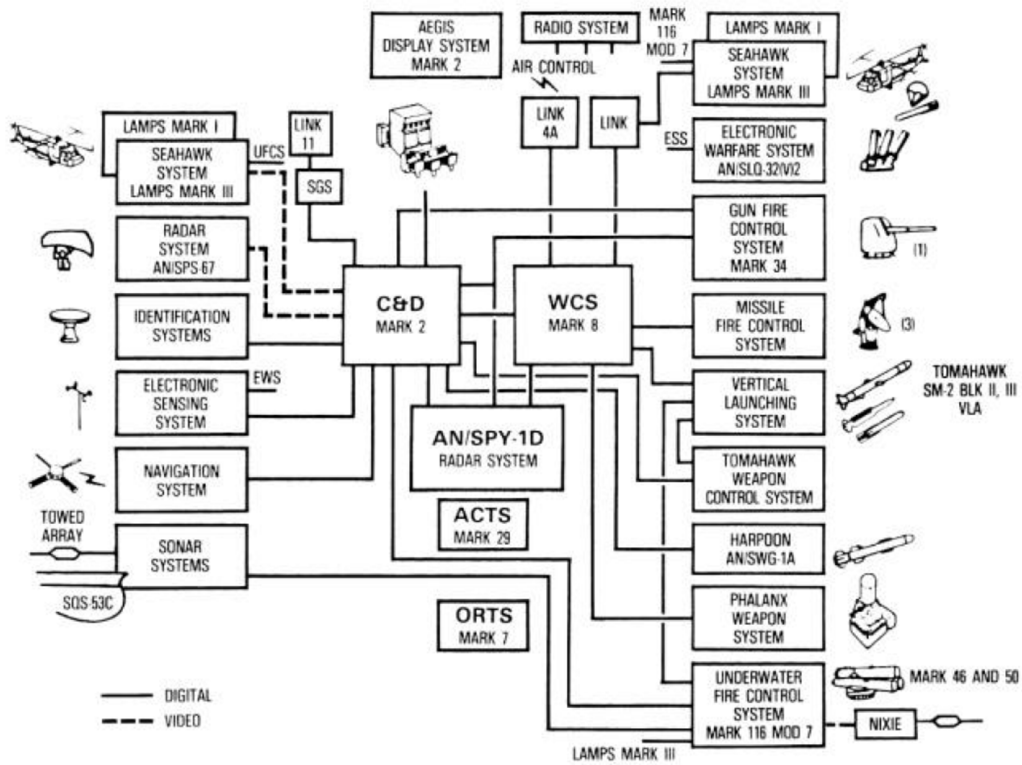

Figure 7. Block Diagram of Aegis System on DDG-51 (from Jane's 2013)

Active phased arrays, on the other hand, feature signal generation in each individual element or small subset of elements (Skolnik 2008). A typical arrangement is shown in Figure 8. This provides several significant benefits. It eliminates the need for extensive waveguides and reduces the signal loss between the signal generator and the transmitter (Al-Rashid 2009). It allows each element to function as a receiver, greatly increasing the number of data points available for the radar's associated processors. It also allows the system to degrade "gracefully," as the loss of an individual transmit/receive element has less impact on system performance than the loss of an entire "subarray" or the loss of the signal generator (Al-Rashid 2009). The active array retains all of the advantages of the phased array over the mechanical antenna.

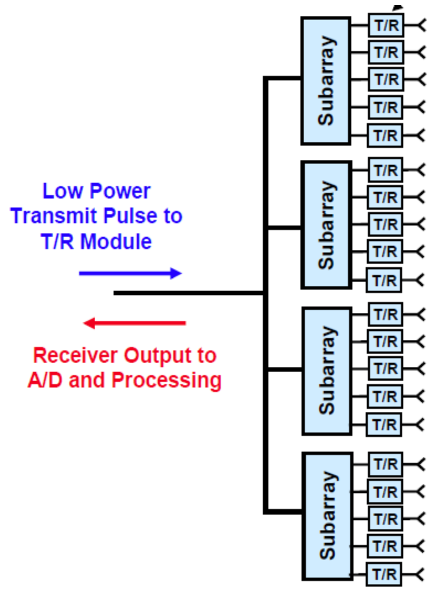

Figure 8. Typical Active Array Arrangement (from O'Donnell 2010, 49)

The Active Phased Array Radar (APAR) is an X-band active phased array radar currently in use by the Dutch and German navies (Thales 2013). It provides many of the same functions as Aegis, although it does not utilize dedicated terminal phase illumination radars. Instead, APAR itself provides terminal illumination by commanding certain T/R elements to illuminate the target at the final stage of the engagement. The APAR utilizes Interrupted Continuous Wave Illumination (ICWI), a variation of a continuous wave beam described earlier, to perform this task (Thales 2013).

The APAR, like the SPY-1, is supported by other onboard sensors. The APAR radar is combined with Thales' Signaal Multibeam Acquisition Radar for Tracking–L band (SMART-L) radar which is an L-band, phased array air search radar (see Figure 9.). The SMART-L is an example of the hybrid phased array radars described earlier. It is trained horizontally by moving the entire array; beamforming and steering are accomplished electronically (Thales 2013).

Figure 9. APAR (left) and SMART-L Radars (from Jane's 2013)

The introduction of the SPY-1/Aegis tandem introduced the first multi-purpose radar into the U.S. fleet. The radar performs air search and track and missile guidance functions as well as being used for surface search and track and gunfire support (NETC 2000). The SPY-1 has been adapted to perform ballistic missile defense (BMD) and is currently the mainstay of short and intermediate range ballistic missile defense for the U.S. and her allies (Jane's 2013). The APAR/SMART-L combination is another example of the multi-use capabilities of the active antenna array concept and it has also been tested in a BMD role (Thales 2013).

The benefits of phased array antennas, combined with ever-increasing computing power, allow modern radar and combat systems to perform extraordinarily difficult military tasks. These range from detection and engagement of sea-skimming anti-ship cruise missiles to discrimination of a ballistic missile warhead from any surrounding clutter at ranges in the hundreds of miles (Jane's 2013; Goldberg 2006). As such, active phased array antennas fit perfectly into the RMA's conception of revolutionizing warfare via technology and thus it is no surprise that such radars had a prominent place on DDG-1000. The next section will examine the development of these radars for DDG-1000.

2. History of the Dual Band Radar on DDG-1000

In conjunction with the start of the DD-21 program in 1998 (described in Section B), Raytheon Integrated Defense Systems (RIDS) received a 5-year, $140 million development contract in 1999 to begin working on the Multifunction Radar (MFR) that was intended for both DD-21 and the future aircraft carrier program, then-designated CVN-21 (DID, 2013). Initial concepts included an X-band multi-function radar paired with an L-band volume search radar (VSR), a configuration very similar to that of the APAR/SMART-L system. The two arrays would operate in their respective frequencies simultaneously, with all radar timing functions, commands, and so forth being performed by a common control unit. The radar controller would essentially perform many of the decision functions that are currently performed by the Aegis combat system. The concept of operations is shown in Figure 10. This would result in even faster processing times than those seen by Aegis. The system would also dispense with the need for separate fire control illuminators. It would also have the potential for use as an electronic warfare system, supplementing the current SLQ-32, and would itself be less susceptible to electronic attack (DID 2013).

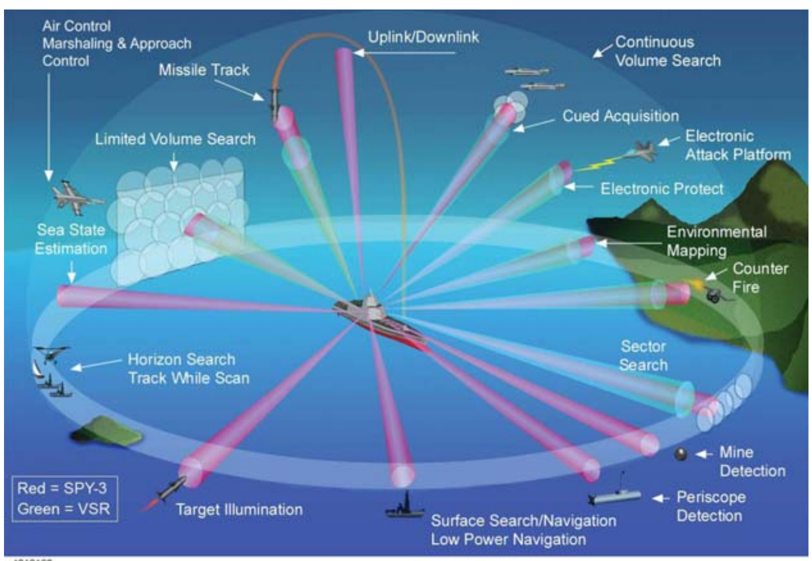

Figure 10. DBR Concept of Operations (from DID 2013)

In 2000, Lockheed Martin, the prime contractor for SPY-1 and Aegis, began an internal development project known as the S-band Advanced Radar (SBAR). The project was primarily intended to demonstrate improvements in BMD performance, a rapidly growing priority for the United States (Friedman 2006). By 2003, Lockheed had begun demonstrations of SBAR at its Moorestown facility (Lockheed Martin 2003). The Navy subsequently announced that the VSR portion of DBR would be S-band instead of L-band, and that Lockheed was to be the subcontractor for the VSR array. Raytheon would remain the prime contractor for the entire system, and was responsible for the common "back-end" of the radar suite (DID 2013). The most important element of integration would be the Radar Suite Controller (RSC) and its associated software. The RSC performs the essential task of coordinating the operations of the radar and allocating the radar's timeline to meet needs (United States Navy [USN] 2012c).

The radar change (and its impact on flow-down requirements such as footprint required in the ship's deckhouse, amount and type of ancillary equipment, software modifications, and so on) were duly noted as a risk in a 2004 GAO report on DDG-1000 (GAO 2004). The change also resulted in schedule delays. The GAO report is also interesting in that it expressed skepticism of the Navy's confidence that all technologies would be mature before installation on the ship. The report also noted that the Navy had no fall-back plans for eight of the ten critical technologies and that schedule slips and additional funding would be the likely result of the over-ambitious schedule (GAO 2004).

The DDG-1000 program plan depended heavily on the development and testing of Engineering Development Models (EDMs) to prove out the many new technologies on DDG-1000, and the DBR was no exception. In 2005, the MFR EDM completed Milestone B testing at the Wallops Island test facility (DID 2013). Milestone B marks the approval for a system to move from the "Technology Development" phase of the acquisition system into the "Engineering and Manufacturing Development" phase (DAU 2011). The Milestone B decision is significant:

> Before making a decision, the MDA (Milestone Decision Authority) will confirm that technology is mature enough for systems-level development to begin, the appropriate document from the Joint Capabilities Integration and Development System (see Chapter 6) has been approved, and funds are in the budget and the out-year program for all current and future efforts necessary to carry out the acquisition strategy. At Milestone B, the MDA approves the acquisition strategy, the acquisition program baseline, the type of contract for the next phase, and authorizes entry into the engineering and manufacturing development phase. The MDA also certifies to the congressional defense committees that the program is affordable, funding is available, market research was conducted, an

> analysis of alternatives was completed, the JROC is in agreement, technology has been demonstrated in a relevant environment, a preliminary design review has been conducted, and the program has a high likelihood of accomplishing its intended mission and complies with all statutory and regulatory requirements. (DAU 2011)

In 2006, the MFR completed at-sea testing onboard the Navy's Self Defense Test Ship (SDTS). In October of that year RIDS announced that it was on schedule with integration of Lockheed's S-band array with the receiver, exciter, and signal processing equipment of their own VSR (DID 2013).

In 2007, RIDS received two additional contracts to continue detailed design and integration of all of DDG-1000's Mission System Equipment (MSE) which included the DBR. In October of 2007, RIDS completed installation of the Lockheed-centered VSR with the MFR located at the Surface Warfare Engineering Facility (SWEF) in Port Hueneme and began an extensive six-month period of integration testing (DID 2013).

The summer of 2008 saw the final reduction of the DDG-1000 program by the Navy and the announcement of the re-start of the DDG-51 production line (as described in Chapter II). Work on the DBR continued, although schedule slips were beginning. In December 2008, a Production Readiness Review (PRR) of the MSE for Zumwalt was completed successfully (DID 2013). A PRR "examines a program to determine if the design is ready for production and if the prime contractor and major subcontractors have accomplished adequate production planning" (DAU 2011, 91). While not strictly a review of technological progress, a "design ready for production" would be presumed to be a design without significant technical problems–indeed, one would expect that it would be tested and proven to meet requirements.

In March of 2009, the GAO issued its annual assessment of major weapons programs. The report specifically described the S-band VSR as "an immature technology" and added:

> Land-based tests of the volume search radar prototype will not be completed until June 2009 — over 2 years later than planned. Upcoming land-based tests will be conducted at a lower voltage than needed to meet requirements—and without the radome. The Navy will not demonstrate a fully capable radar at its required power output until testing of the first production unit in 2011. Partly due to delays, the volume search radar will

> not be installed during deckhouse construction as initially planned. Instead, installation will occur in April 2013—after the Navy has taken custody of the ship. (GAO 2009)

The report seemed to fly in the face of the previous year's PRR (which is chaired by the Navy). Delays with VSR also had potential impacts on the future carrier program (known by this time as the CVN-78 program). The 2010 GAO report noted that the VSR had "…progressed in maturity" but that the radar would still not be fully tested until after it was installed in DDG-1000 (GAO 2010, 55). In May of 2010 Raytheon announced that it had simultaneously tracked targets with both the S- and X-band portions of the radar during continued EDM testing at Wallops Island (DID 2013).

The July 2008 reduction in ship numbers (and subsequent budget requests with reduced funding) resulted in a Nunn-McCurdy breach for the program. As a result of that breach, the Navy looked for ways to immediately reduce the procurement cost of the hulls. In June of 2010, the Navy made the decision to remove the VSR from DDG-1000 (O'Rourke 2011). The VSR was not cancelled; the entire DBR will be installed on CVN-78. The removal of the VSR is estimated to save roughly $100 million for each of the three DDG-1000 hulls. Funding for integration and testing activities was also lowered for DDG-1000, although maintained for CVN-78 (the later "need date" for CVN-78 allowed those activities to be spread across further years of budget requests) (DID 2013). In the end, the move was justified by the DDG-1000 program manager in this way: "…we don't need the S-band radar to meet our requirements…you can meet requirements with [the] X-band radar with software modifications" (O'Rourke 2012, 56).

Although the VSR was removed from DDG-1000 design, the space and weight reservations designated for installation of the equipment will remain. This could allow for future expansion of the MFR, if the MFR was further developed into a BMD version, or future installation of the new AMDR (DID 2013).

In addition, the MFR will have to be modified to perform many of the long-range search functions that the VSR was to have performed. Such an alteration of mission and requirements after nearly ten years of development was not without impact. These will be described in Chapter IV. The modifications were also not without cost, although the

Navy and the Under Secretary of Defense for Acquisition, Technology and Logistics (USDAT&L) believed "…the estimated cost of the MFR software modification to provide the volume search capability will be significantly less than the estimated procurement costs for the VSR…" (O'Rourke 2012, 56).

The MFR will be installed on all three DDG-1000 ships; contracts for procurement of the radars were issued in 2007 and 2009 (DID 2013). A full DBR (including MFR and VSR) has been funded for installation in CVN-78. It remains uncertain if DBR will be installed on future carriers. RIDS is still performing software modifications to implement volume search functionality on the MFR (DID 2013).

E. MISSILE IMPLEMENTATION ON DDG-1000

DDG-1000 has a requirement to employ missiles for ship self-defense (O'Rourke 2004). The missiles originally chosen for implementation on DDG-1000 were the Standard Missile (SM) 2 Block III-B and the Evolved Sea Sparrow Missile (ESSM). This section will briefly describe the characteristics and operation of the two missiles and the modifications required to make them compatible with the MFR. The program to accomplish this integration of ESSM and SM into DDG-1000 is known as the Joint Universal Weapons Link (JUWL) program or the ICWI-JUWL program. It is important to note that for both missiles, the JUWL effort was supposed to result in a technical data package describing the new component, several Inert Operational Missiles (IOM), and a Missile Communication Test Set (MCTS). The program did not include funding for integration efforts with the combat system, funding to transition the design to production, or any flight testing of the hardware (Raytheon 2012). Those efforts were expected to be scheduled and performed under the cognizance of the related missile programs, and funded through their budget requests or existing funding.

1. JUWL Program Organization

JUWL was not implemented as a stand-alone development program. It was organized as a project under the direction of the Program Executive Office (PEO) for Integrated Warfare Systems (IWS) Surface Ship Weapons (Office Code 3.0). The project manager for the effort was assigned from office code 3A (Standard Missile) and the funding for the project was added as a technical instruction (TI) to the existing engineering and technical services contract for Standard Missile (Raytheon 2013). The prime contractor is Raytheon Missile Systems (RMS) in Tucson, Arizona. By necessity, the program needed to interact with the PEO for DDG-1000 and the PEO for DDG-1000 combat systems as well as the prime contractor for development of the MFR and the DDG-1000 combat system, Raytheon Integrated Defense Systems (RIDS) in Tewksbury, Massachusetts. Figure 11. shows the program organization.

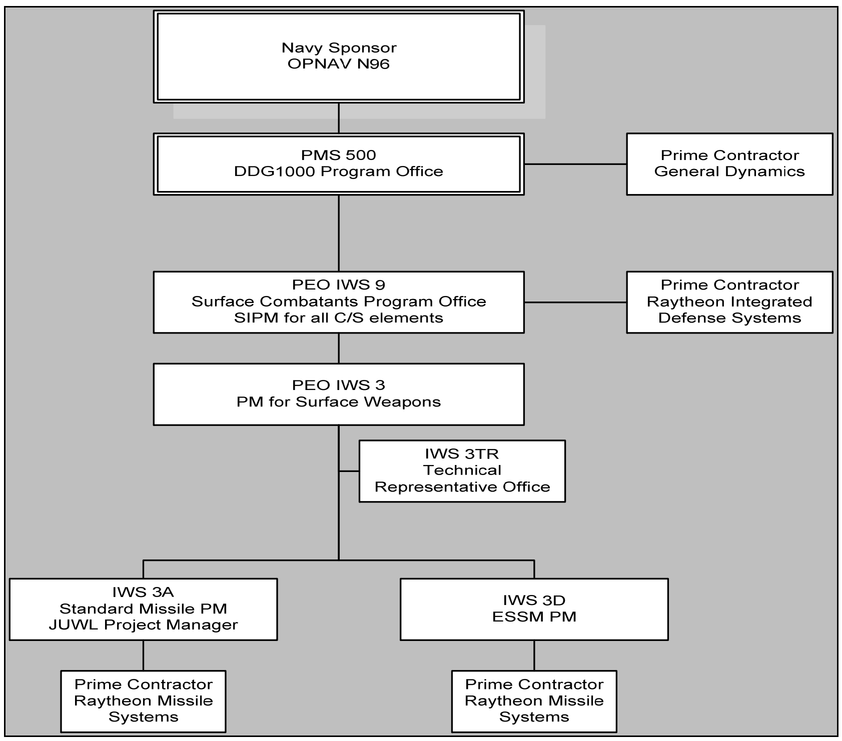

Figure 11. JUWL Project Organization

IWS 9 served as the Systems Integration Program Manager (SIPM) for all DDG-1000 combat system elements. PMS 500 is the overall program manager.

The JUWL Statement of Work (SOW) directs the contractor to develop link and guidance functionality for ESSM and SM to operate from DDG-1000. It also specifies that all other missile requirements are unchanged. In other words, ESSM and SM requirements are not altered by the missile’s implementation with DDG-1000 unless it is clearly called out in an interface document. Indeed, the interface documents in use on

DDG-1000 are legacy documents from the Aegis program. For instance, the launcher interface document is the Mk41 VLS interface document–despite the fact that DDG-1000 uses the new Mk57 launcher. While ostensibly identical to the Mk41, such "identicalness" has not been tested in a practical environment to date.

2. ESSM

ESSM is an evolution of the NATO Sea Sparrow missile. Sea Sparrow is a medium range, semi-active homing, ship self-defense missile developed in the late 1960s and early 1970s (USN 2012a). Sea Sparrow uses the TAS (Doppler L-band) radar for initial detection of targets and the X-band Continuous Wave (CW) Mk95 director for target illumination. The missiles are fired from the Mk29 above-deck eight-cell trainable launcher (Friedman 2006). Figure 12. depicts the elements of the Sea Sparrow system. From left to right; they are the Mk29 launcher, the TAS, and two of the Mk95 illuminators.

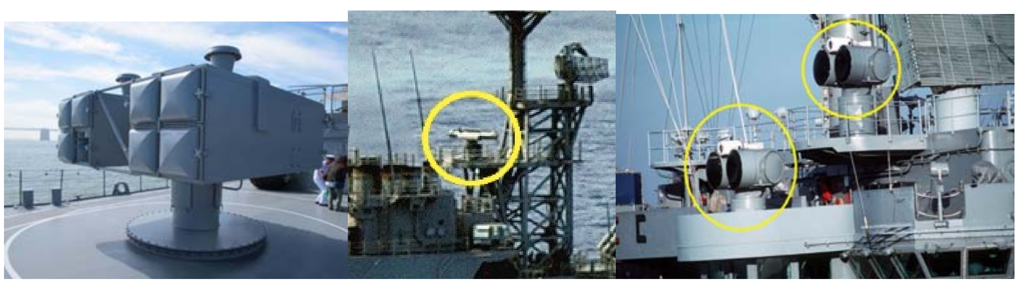

Figure 12. Components of the SeaSparrow System

ESSM has significant improvements over SeaSparrow, including improved missile kinematics and a vertical launch capability. The ESSM also features updated electronics, allowing it to receive mid-course guidance and terminal illumination from the S-band SPY-1/Aegis system or the X-band APAR system (USN 2012a; Raytheon 2013). The Aegis configured missiles are capable of uplink and downlinks; the APAR missiles are uplink only. The ESSM is currently launched from four different launchers (the trainable Mk29 and the vertically-launched Mk41, Mk48 and Mk56) and interfaces with ten different combat systems (the Mk57 NSSMS, Aegis, APAR, and other country-specific systems). Each combat system and radar combination requires a different variant of the ESSM missile. For instance, an ESSM fired from the original SeaSparrow system does not feature the thrust vector apparatus required for vertical launch and does not contain midcourse guidance functionality (DID 2013). Figure 13. shows the various stages of ESSM operation.

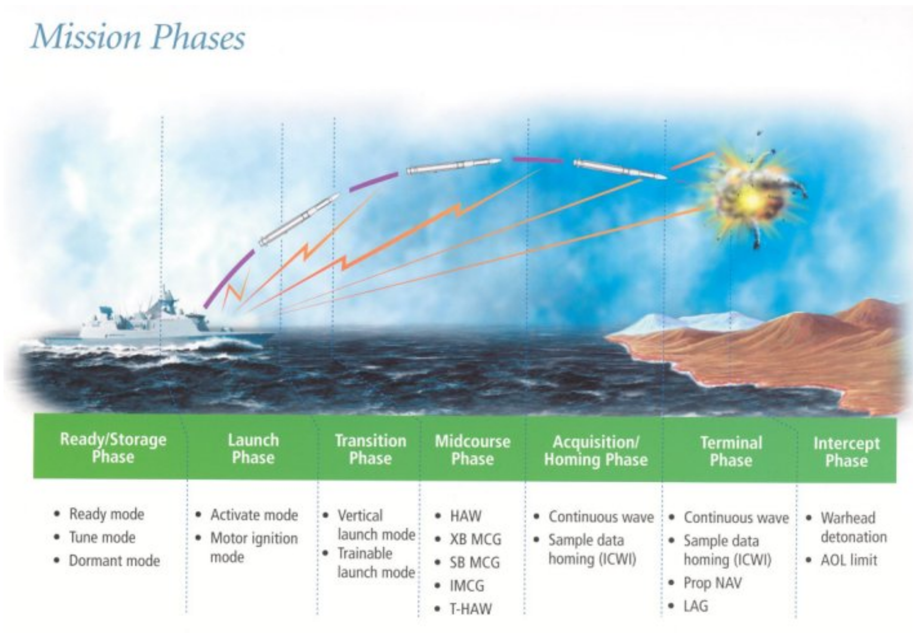

Figure 13. ESSM Operation (from DID 2013)

The ready/storage phase denotes the period onboard the ship before the missile is first activated for firing. The missile receives initial target information before its motor is ignited and the ESSM leaves its launcher. The transition phase is the period in which the missile conducts a pitch over maneuver to change from a vertical flight path to a horizontal or nearly horizontal flight path to intercept its target. During the midcourse phase, the ESSM continuously adjusts its flight path using information transmitted from the ship to intercept the target. In the acquisition/homing phase, the missile's onboard seeker begins its search for the target by detecting RF energy, transmitted by the Aegis' dedicated illuminator or the APAR's ICWI waveform, reflected from the target. Once the target is acquired, the missile's autopilot adjusts its flight path to intercept the target as closely as possible. The terminal phase begins when the ESSM and missile are entering very near proximity; at that time the illumination from the signal shifts to a continuous signal, allowing the ESSM to have the most rapid updates possible in order to maneuver as close to the target as it can. The missile's Target Detection Device (TDD) will detonate the warhead at the optimal time to achieve the maximum chance of destroying the target.

The ESSM, like SeaSparrow, is not an area defense weapon. It was designed strictly for ship self-defense and has limited ability to protect other vessels. Although its primary targets are anti-ship cruise missiles, it does have a surface to surface mode and can also be employed against slower air targets (USN 2012a).

The ESSM missile (Figure 14.) is composed of a seeker, guidance section, warhead, transition section, and propulsion section.

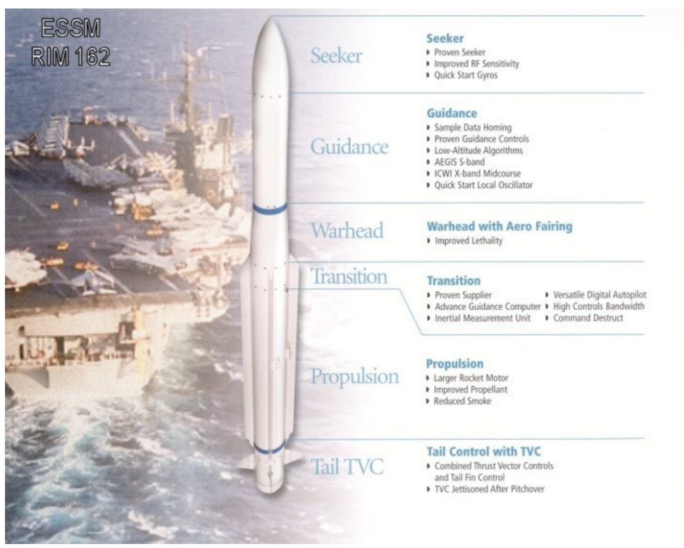

Figure 14. ESSM sections (from DID 2013)

The antennas for data link operations are contained in the transition section. Figure 15. shows the main sections of this internal arrangement:

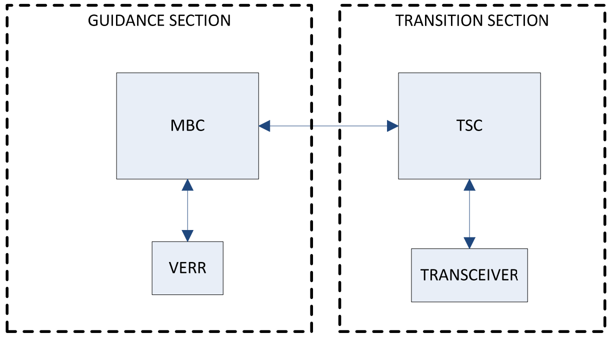

Figure 15. Data Link Components

Figure 16. shows an expanded view of the internal arrangement of ESSM, including interfaces with the guidance section and launcher.

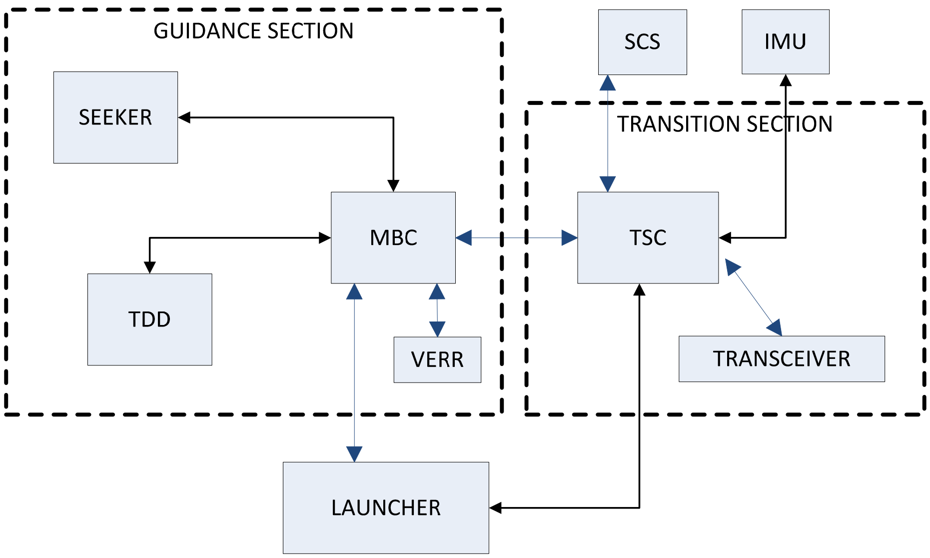

Figure 16. ESSM Guidance Components

As described in the phases of flight, the missile receives target information and own ship position before launch. After launch, the missile receives target position and possible maneuvering commands from the ship via the transceiver. The target position information is relayed to the MBC, where the MBC uses the information to issue commands to the seeker head to point at the target. The TSC processes information from the Inertial Measuring Unit (IMU) and uses the IMU data, along with uplink information, to update the missile's position. That calculation is compared to the target information by the

MBC, which in turn issues steering commands to the missile's control surfaces via the TSC to the Steering and Control System (SCS). The SCS also returns feedback to the TSC. The ESSM will begin to search for the target at a predetermined time or when ordered to so by the ship. When the ESSM is close enough to the target, the illuminator changes to continuous transmission and the missile executes the terminal portion of the flight.

Modifying ESSM for JUWL required five major areas of effort:

- Replacing the S-band transceiver with an X-band transceiver
- Replacing the antenna associated with the transceiver
- Modifying the TSC software
- Modifying the MBC software
- Modifying the VERR software (Raytheon 2012)

Because ESSM already had a variant compatible with an X-band ICWI waveform, the ESSM portion of the JUWL program had fewer fundamental changes to perform in order to produce a missile that would be compatible with DDG-1000. There were only software changes needed to support a new transceiver/antenna combination and software to support the new uplink/downlink data formats of the MFR. The program did not have to make any changes to the guidance algorithms in the MBC. The DDG-1000 ESSM Concept of Operations (CONOP) for a missile flight was in fact based on the ESSM APAR CONOP. The ESSM is the first of the two missiles that will be integrated, tested, and fired from DDG-1000 during her Initial Operational Test and Evaluation (IOT&E) period (DID 2013).

3. SM-2

The Standard Missile (SM) is an outgrowth of the Navy's earlier Terrier and Tartar missile programs. It is a "medium to long" range (up to 90 nautical miles), semi-active homing, area air defense missile (USN 2012b). There have been many variants of the missile produced to date; some were required for use on different launchers and others incorporated performance improvements (Friedman 2006). The U.S. Navy has retired earlier versions of the SM-2, although other nations still use them (as well as the earlier SM-1 missile) (Jane's 2013).

The U.S. Navy currently employs the SM-2 Block III, SM-2 Block IIIA, and the SM-2 Block IIIB (USN 2012b). Block III featured flight trajectory improvements over earlier versions and the Block IIIA featured an improved warhead. Block IIIB incorporated maneuverability improvements via a software upgrade and also incorporated an infrared sensor for terminal homing. The SM-3 missile is a much larger variant used for ballistic missile defense missions. SM-6 is an extended range variant which also features an active seeker, enabling improved performance against certain target types and full utilization of the Navy's improving Cooperative Engagement Capability (CEC). It may also eventually be featured in a terminal phase BMD role (DID 2013).

An Aegis SM engagement follows a pattern similar to that of an Aegis ESSM (see Figure 17.). The ship's sensors detect and track a target and the combat system relays target position data to the missile. The missile is launched vertically and maneuvers to bring itself to the desired flight path. The missile receives S-band data uplinks and continues to maneuver to close on the target. It also can downlink information when queried. Terminal phase illumination is provided by the SPG-62 illuminators on the ship (NETC 2000).

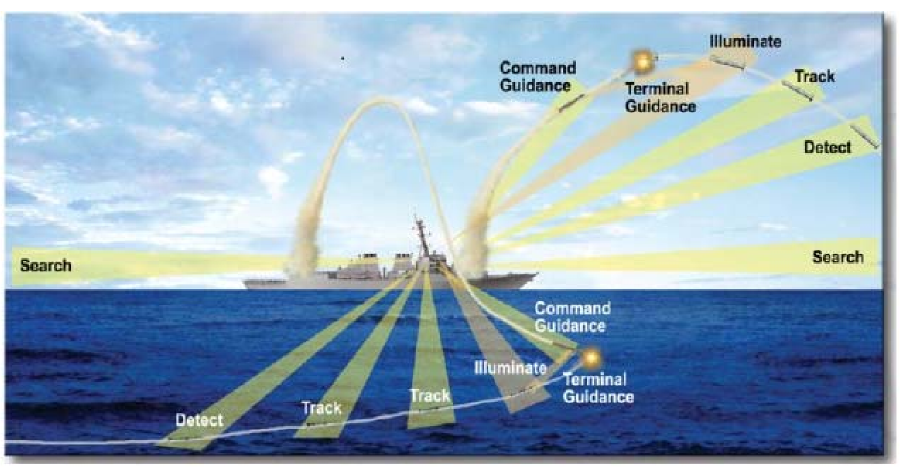

Figure 17. Typical Standard Missile Engagement (from Raytheon 2013)

SM-2 Block IIIB required significant work to make the missile compatible with the DDG-1000's MFR. Significant efforts included:

- The new frequency and waveform required modification to the missile's existing receiver (referred to as Plate 1)
- Modification of the missile's transmitter (Plate 3)
- Modification of the encoder/decoder (Plate 4)
- Complete redesign of the existing digital signal processor (Plate 2)
- A new software build to support the ICWI waveform, transmit and receive link messages to the MFR, and include new guidance algorithms for the missile (Raytheon 2013)

A modernization effort for Plate 2 had already begun to support the Standard Missile program as a whole, addressing obsolescence issues and inserting components to accommodate future growth. It was known as the Digital Signal Processor–Modernization or DSPM. JUWL was directed to integrate with that effort to ensure that the DSPM would meet JUWL requirements (Raytheon 2013).

The effort required to make SM compatible with DDG-1000 was not trivial. It required significant hardware and software efforts. The SM portion of JUWL is scheduled for its critical design review (CDR) in late summer of 2014 (Raytheon 2013).

4. Missile Deliverables and Changes

The JUWL effort had several significant events affect the program since it was initiated. First, the original intent for the SM JUWL was to add X-band functionality to the missile but retain S-band compatibility. This would result in a truly "universal" component, reducing costs and limiting the amount of configuration changes in the SM program. This requirement was dropped in 2010 (Raytheon 2013).

In 2010, the Navy restructured the entire DDG-1000 effort as a result of the Nunn-McCurdy breach and subsequent budget request changes. As noted, funding for integration of the VSR and MFR was cancelled; that funding had also been used to support the JUWL effort. In January of 2011, no additional funding had become available to support the JUWL TI and the prime contractor stopped the effort and re-assigned or released the engineering staff working on the project (Raytheon 2011). Additional funding was finally allocated in June of 2011 and RMS began re-assembling its team. This delay resulted in some significant schedule slip for both ESSM and SM. While this was certainly not the Navy's intent when it restructured the program in response to Nunn-McCurdy, it had significant impact on the prime contractor's development effort.

In the summer of 2012, the Navy made the decision to change the DDG-1000 SM missile from the Block IIIB type to the older Block IIIA type (Raytheon 2013). This had significant impact because the Block IIIA had different hardware and software from the IIIB. In particular, the IIIA does not contain the IR hardware for terminal phase, does not contain the software-driven Maneuverability Upgrade (MU), and is equipped with a different TDD. All of these changes affect JUWL. The absence of the IR hardware altered the physical layout of the plates that JUWL was designing and also affected the guidance software. The different TDD also affected guidance as the missile may need to fly different flight paths against different targets. The absence of MU could also have affected guidance; however, the program later decided to include MU functionality in the JUWL software build (Raytheon 2013).

Finally, the MFR itself has changed in order to accommodate the addition of some of the functionality of the deleted VSR. The heart of a multi-function radar is the management of the radar's resources. As described earlier, a multi-function radar performs all of the functions previously performed by multiple conventional radars. Thus, a multi-function radar must direct its RF energy, receive signals, process those signals, and then potentially redirect its RF energy based on its analysis. The radar may need to direct some RF energy toward midcourse guidance of a missile, and may also need to illuminate a target for the terminal phase of an engagement, while simultaneously tracking multiple other targets and searching for new targets.

Consider the following example. A multi-function radar is operating in a general search mode (which is pre-established, based on the operating environment and expected threats). The radar receives return reflections from a certain bearing, range and altitude which I will call position A. The radar analyzes these returns with predetermined algorithms and based on the strength and number of repeated reflections determines that the reflections are, in fact, a target. It then implements "tracking" algorithms which radiate RF energy to ensure that the radar continues to receive reflections from the target. The algorithms use the analysis of the reflections to predict the location of the target allowing for error. Faster targets require more reflections in order to keep those predicted positions accurate. Hence the radar is constantly predicting position B for the target, then position C, and so on. There are time delays associated with the receipt of reflections, processing, predictive calculations, commands to the antenna to radiate toward a certain new position, and the reiteration of the process. The delays can be significant, even if those times are measured in fractions of a second, when the targets are moving at high speed and/or are constantly changing course or speed. When a radar element is directed to perform a certain function, it cannot perform another. Thus, if a group of elements are radiating to illuminate a target for the terminal phase of an engagement, they cannot radiate to search in another sector.

This entire process is radar resource management. It is the key improvement of the multifunction radar over a system utilizing conventional radars. A conventional radar cannot perform these re-directed tasks. The combat system is limited to tracking targets as fast as the radars can perform and can “command” only a very limited set of sensors.

A single target is a trivial problem for a multi-function radar, given the computing power available to perform the calculations and issue the subsequent commands. However, the system can be overwhelmed or “saturated” by high numbers of targets and conflicting demands for resources.

The following brief example highlights the complexity of the software needed to coordinate all of the possible combinations of functions for a multi-function radar operating in a target dense combat scenario. Radar resource management, also referred to as radar timeline or radar timeline budget, is the key consideration for effective employment. Therefore, when the MFR program was directed to implement new functionality after almost ten years of development, it was a major change. Some of the changes have only recently been conveyed to the JUWL program. The most significant impact may be that the MFR has “maxed out” its radar timeline in certain scenarios and therefore may need to consider tactical employment changes to support any potential changes in the future.

F. SUMMARY

Most of the new combat systems developed for DDG-1000 have experienced significant technical challenges or have seen significant changes in scope. The AGS experienced several years of delay in developing a suitable projectile. Although not discussed in this paper, the DDG-1000 Undersea Warfare (USW) systems had developmental delays and technical challenges (DID 2013). The DBR experienced delays in developing the S-band VSR, which was subsequently removed from the ship. That removal drove changes into the MFR, which is still in the process of incorporating changes and assessing their impact on performance and radar timeline. The JUWL program had to develop new hardware and software for both ESSM and SM and changes to the MFR may yet have significant impact on both missiles.

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IV. PROCEDURES, STANDARDS AND BEST PRACTICES

A. INTRODUCTION

The federal government, the Department of Defense, and the Navy have enormous numbers of legislative mandates, governing regulations, and policy directives concerning the development of systems for government use. This thesis will focus only on DOD-specific directives and regulations.

This chapter will briefly describe the DOD's framework for acquiring systems. It will also list key concepts of systems engineering that contribute to successful system development. It will also examine current management organizational constructs that have been created in an attempt to help management personnel, both civilian and military, succeed in this challenging environment.

B. THE DEFENSE ACQUISITION SYSTEM

The Defense Acquisition System (DAS) is intended to produce successful acquisition programs. A successful program "…places a capable and supportable system in the hands of users (the warfighter or those who support the warfighter), when and where it is needed, at an affordable price" (Defense Acquisition University (DAU) 2010, 5). The term "Defense Acquisition System" usually refers to the specific rules governing the administration of acquisition programs in the DOD, but is sometimes more generally applied to the interactions of Congress, the executive branch, and industry (DAU 2010). For purposes of this thesis, DAS will refer to the specific administration of military programs and the term "acquisition environment" (AE) will refer to the broader interaction of Congress, the President, industry, and the respective influences of public opinion, media, and so forth (see Figure 18.

The executive branch includes the presidential administration, the uniformed services, and all civilian staff in the DOD. The legislative branch includes all Representatives and Senators as well as their personal staffs and the full-time Congressional staff. Industry encompasses all of the major defense industry corporations and smaller businesses supporting the defense industry or the DOD (DAU 2010).

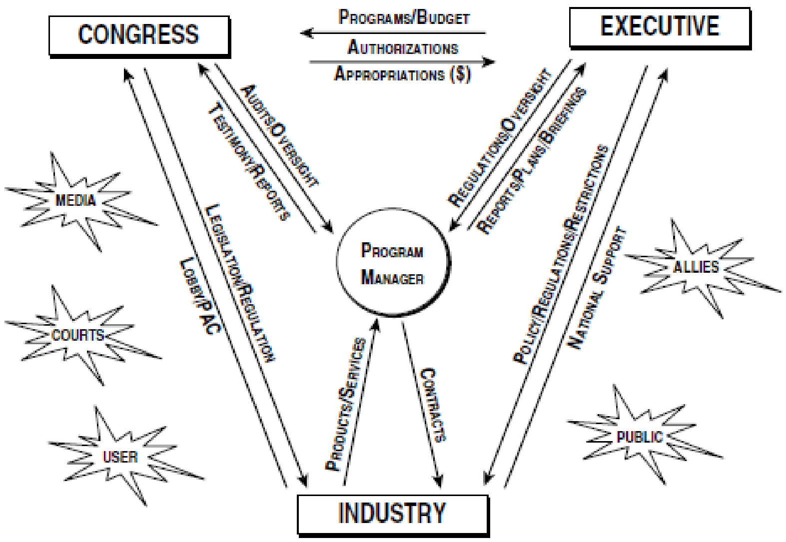


Figure 18. The Acquisition Environment (from DAU 2010, 2)

The DAS is just one of three so-called "decision support systems" created by Congress and the Executive Branch to determine what systems should be acquired, how they will be paid for, and how they will be produced (see Figure 19. The others are the Planning, Programming, Budgeting and Execution (PPBE) process and the Joint Capabilities Integration and Development System (JCIDS) (DAU 2010, 18).

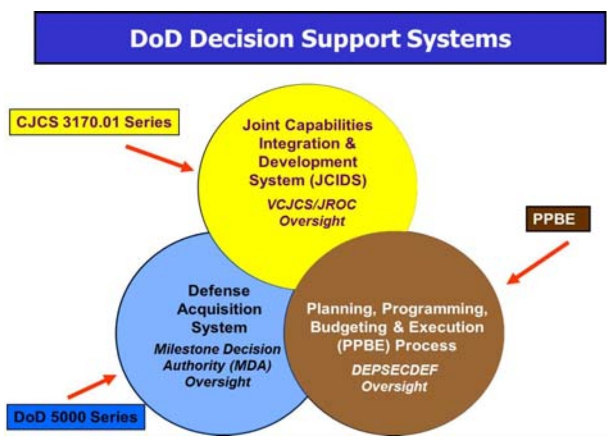


Figure 19. Three Decision Support Systems (from DAU 2013, 6)

The JCIDS process analyzes projected military capability needs and shortfalls which are submitted by the various regional and functional Combatant Commanders (COCOMs). If the JCIDS analysis determines that there is a need for a new military system to meet these capabilities or shortfalls, the DOD names a Defense Acquisition Executive (DAE) to oversee the fulfillment of the requirement. The basic JCIDS process is shown in Figure 20.

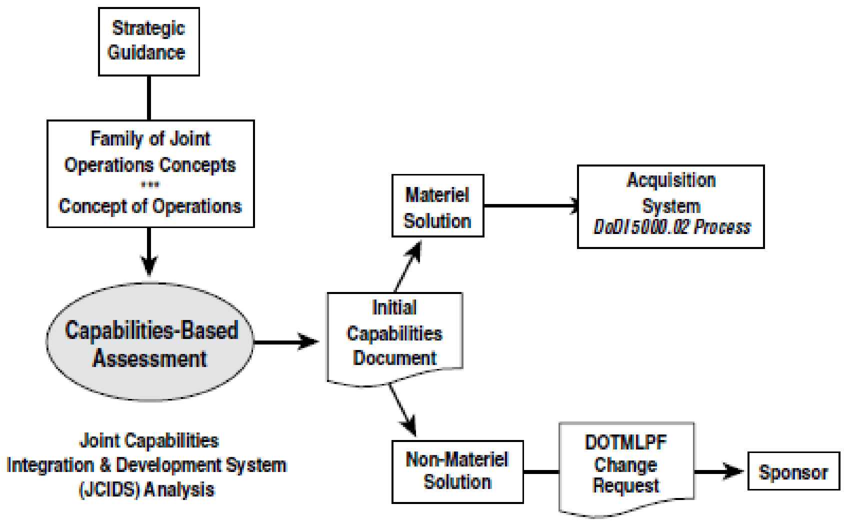


Figure 20. JCIDS Overview (from DAU 2010, 36)

The DAE, in turn, determines the proper chain of command to manage the development of the new system and establishes the responsible program office (see Figure 21. The DAS allows for a great deal of flexibility in organization, and not every program will align neatly with the chain shown in the figure. Because of cost, national strategic importance, or other reasons, some programs will not feature a Program Executive Office (PEO) between the program manager and the Component Acquisition Executive (CAE). Conversely, for service-specific or less costly programs, the DAE may delegate authority to the service itself.

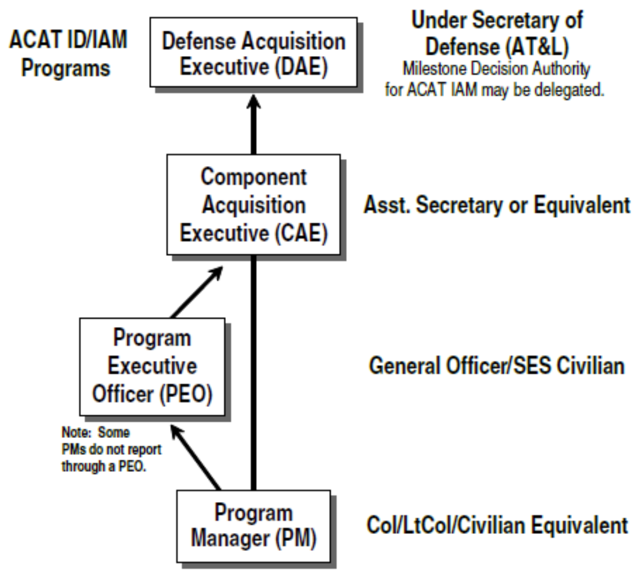


Figure 21. Generic Acquisition Chain of Command (from DAU 2010, 25)

The DAS is perhaps best described as a phased sequence of technological development intended to produce a successful system. It is a management construct and is designed to be flexible in application. For example, not every program begins at the first stage (material solution analysis). Some programs which feature a proven design applied in a new environment could enter at a later phase (DAU 2011).

Spaced throughout the various phases are a series of demonstrations, technical reviews, and programmatic "milestone" decisions. A high-level view of the DAS is shown in Figure 22. The intention of the DAS is to ensure that the original requirements of the system are met by its design. It is also intended to ensure that *all* aspects of a system throughout the system's anticipated life cycle are addressed in the early stages of design and development.

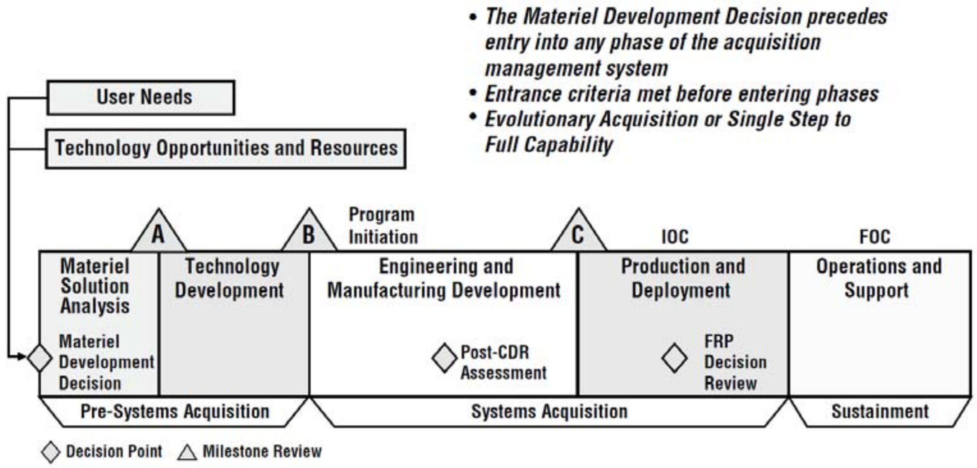


Figure 22. DAS Overview (from DAU 2010, 41)

For example, design of the system should take into account the anticipated maintenance cycle of the system, or conversely, the system should be designed to meet the maintenance requirements needed by the warfighter. These decisions can have an enormous impact on system cost and development time. Continuing with the maintenance example, consider the implications of maintenance of a shipboard diesel engine compared with a surveillance satellite. A great deal of diesel engine maintenance and repair can be performed by the ship's engineers, and the engine's consumables and spare parts can be introduced into the existing ship supply system. The satellite, on the other hand, will likely never receive a maintenance visit of any kind. Hence the satellite must be designed and manufactured to an enormously higher standard for reliability, workmanship, and overall quality. Such demands are commensurately more expensive.

Other examples of system design which should be addressed in the early stages of design include (Blanchard and Fabrycky 1998):

- Required Performance
- Physical characteristics
- Maintenance concept
- Reliability
- Transportability
- Human Factors (ergonomics)

- Safety
- Producibility
- Testability
- Facilities
- Support personnel
- Disposability
- Obsolescence
- Future improvements
- Packaging, handling, storage and transportation
- Environment

The list shown is by no means complete. Many factors could be related; consider how physical dimensions of the system could be limited by the intended transportation method. This consideration of the total life cycle of a design, known as "life-cycle engineering," is a hallmark of the systems engineering process and one of the essential elements for design success (Blanchard and Fabrycky 1998).

The PPBE system is the method by which the DOD produces its budget. It is a complicated process and will only be briefly described. The process was originally implemented by Secretary of Defense Robert McNamara in 1962 (Army Force Management School (AFMS) 2011). The key feature of McNamara's new process was an attempt to plan for and control change. Instead of producing and submitting single year budgets independently (as the services had done previously), the services now submitted five year projections to the Office of the Secretary of Defense (OSD) to be consolidated into a Future Years Defense Plan (FYDP). This is the main tool by which OSD (and by extension the president in his role as commander-in-chief) determine the size and type of military forces to procure and operate to meet its strategic needs (AFMS 2011). The FYDP is probably best considered as a five-year spending plan, which the DOD uses to submit its annual budget to Congress. Once the budget is enacted into law, the DOD then spends (executes) the budgeted funds.

When changes to the five year plan are deemed necessary, the services submit change requests to OSD for consideration. To manage the number of change requests produced, the OSD issues strategic and budgeting guidance to the services each year which highlights DOD priorities and adjustments to overall strategy. Thus, the PPBE system is a never-ending cycle of planning, spending, and accommodating changes in national strategy and military priorities that in turn affect budgets.

Each service has an internal process to produce its five year inputs as well as the current years' budget requests. This is driven by OSD guidance as well as by the service's assessment of its needs to meet national strategic guidance. These budget requests are consolidated by OSD and flow into the president's budget submission to Congress (see Figure 23.).

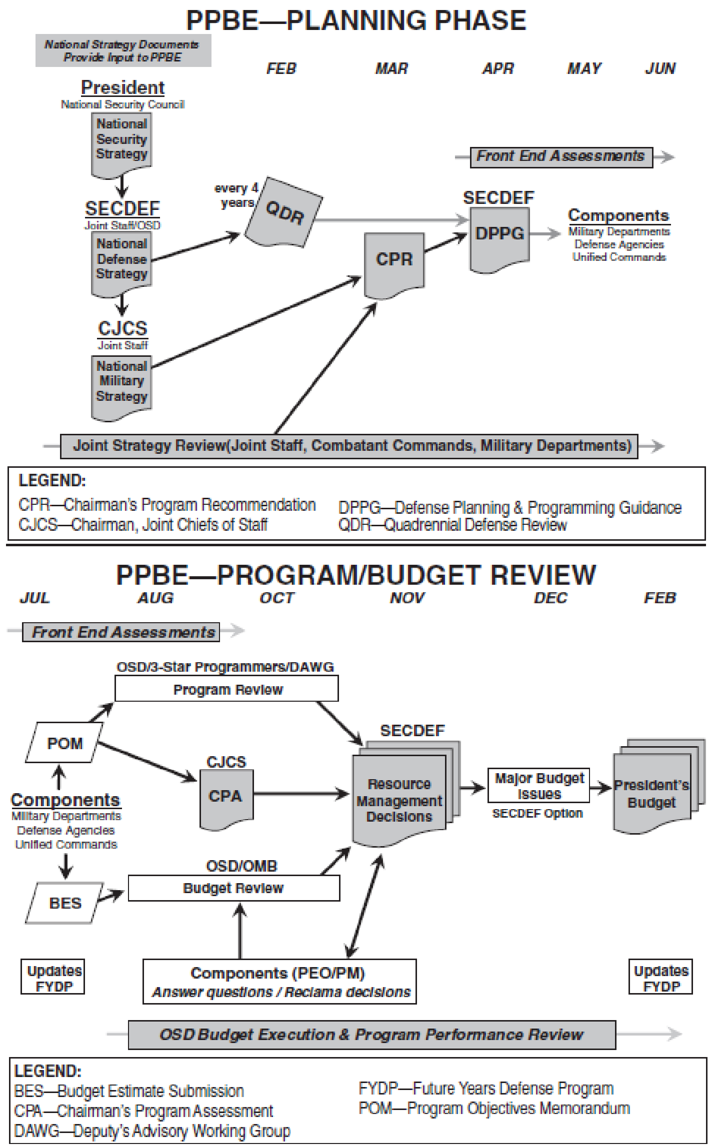


Figure 23. PPBE Service & OSD Actions (from DAU 2011, 20)

Congressional action on the budget follows the process shown in Figure 24. Congress often disregards the recommendations of OSD and the individual services in order to fund programs it deems important or cancel programs it deems too costly. These Congressional decisions then affect the program estimates and budgets for subsequent years.

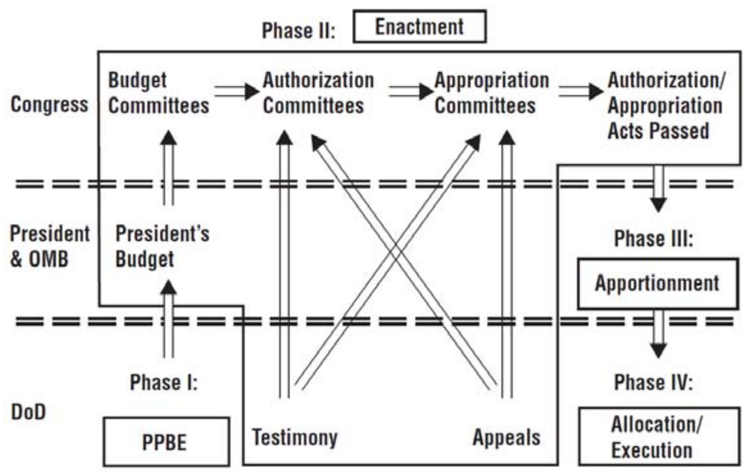


Figure 24. Congressional Action on the Budget (from DAU 2011, 21)

This brief summary does not capture the many intricacies of budgeting, scheduling, and reporting needed by the DOD to operate in the acquisition environment.

The complex interactions of the PPBE, JCIDS, and DAS are one of the main reasons that the DOD employs such a vast bureaucracy. Cost analysts, contracting specialists, and administrators are needed to fulfill the voluminous reporting and budgeting documentation needed by thousands of individual acquisition programs across all the services. A quick glance at the latest version of the "Integrated Defense Acquisition, Technology, & Logistics Life Cycle Management System" chart, known as the "wall chart" or "horse blanket" chart, will give some idea of the multitude of activities and procedural steps faced by even a relatively small-scale acquisition program (DAU 2013, 11).

The DOD recognizes this complexity and has taken steps to aid the services and their respective program offices in navigating through the process. The next section will discuss the DOD's systems engineering infrastructure and describe how the infrastructure is designed to aid in the design, development, and production of effective and affordable military systems.

C. SYSTEMS ENGINEERING IN THE DEPARTMENT OF DEFENSE

The DOD has recognized the importance of implementing robust systems engineering principles into the DAS and into acquisition program management. The OSD established an additional Office of the Deputy Assistant Secretary of Defense for Systems Engineering (ODASD-SE) in order to provide guidance and oversight for implementing quality systems engineering in the DOD. The Office's mission statement is:

> …to develop and grow the Systems Engineering capability of the Department of Defense—through engineering policy, continuous engagement with Component Systems Engineering organizations, and substantive technical engagement throughout the acquisition life cycle with major and selected acquisition programs. We apply best engineering practices to:
>
> - Help program managers identify and mitigate risks
> - Shape technical planning and management
> - Support and advocate for DOD Component initiatives
> - Provide technical insight to OSD stakeholders
> - Identify systemic issues for resolution above the program level. (ODASD-SE 2013)

Numerous studies have determined that disciplined implementation of systems engineering principles, which can fall under Blanchard and Fabrycky's general term of "life cycle engineering," correlate directly to improved project performance in terms of cost, schedule, and product performance. For example, a 2012 study conducted by the Systems Society of the International association of Electrical and Electronics Engineers (IEEE) and the National Defense Industrial Association (NDIA) showed that only 15% of projects that failed to apply thorough and early SE achieved established project success criteria. The projects that did implement early and effective SE achieved a 57% success rate. The difference was even greater for those projects deemed to have a high complexity rating (Elm and Goldenson 2012, 74). This is not a new result. The related disciplines of systems engineering and project management have achieved near-universal acceptance in engineering and industry for over 60 years (Stuckenbruck 2008; Honour 2013). As we shall see in later sections of this thesis, however, acceptance does not automatically translate into effective application.

Congress also established a system of professional education for personnel employed in the DAS with the passage of the 1990 Defense Acquisition Workforce Improvement Act (DAWIA). The law stemmed from the 1986 Packard Commission Report that concluded military and civilian officials involved in defense procurement were typically undertrained and/or inexperienced (Fox 2011). DAWIA established a robust system of training and certification in a variety of career fields for both uniformed and civilian personnel in the DOD (DAU 2010).

ODASD-SE continues to stress the development of a professional acquisition workforce. Consider the following statement from the ODASD-SE:

> One of our greatest challenges may be in our approaches to building great people and teams and improving how we recruit, grow, and mature the technical and systems engineering professionals who will successfully deliver today and tomorrow's critical defense systems. We are working closely with the DOD Components to enhance the capability and capacity of the technical management workforce. As an example, we are identifying workforce competencies crucial for executing systems engineering and production, quality, and manufacturing functions within acquisition programs. (ODASD-SE 2013)

The *Defense Acquisition Guidebook* includes a significant chapter on systems engineering and all of the services have their own systems engineering guidance for program managers. For example, the various naval systems commands combined to issue the *Naval Systems Engineering Guidebook* and the Air Force publishes *The Early Systems Engineering Guidebook* and the *Systems Engineering Primer & Handbook*. These guides cite academic and professional literature concerning SE definitions, techniques, and best practices. Examples include the *Systems Engineering Handbook* published by the International Council on Systems Engineering (INCOSE) and the IEEE *Systems Journal*. ODASD-SE maintains a standards and specifications database of over 111,000 documents (ODASD-SE 2013). It also provides a technical interface with the International Organization for Standardization (ISO).

The creation of systems engineering directorates in OSD and all the services, as well as the voluminous amount of SE guidance for program managers and acquisition professionals, is testament to the importance that the DOD attaches to effective SE as a means to "solve" the problems that have plagued military acquisition. Given that emphasis, it is important to describe some of the SE principles that lead to program success.

1. Requirements

Establishing requirements that are clear, valid, achievable, and remain constant is one of the most commonly cited necessities for the completion of a successful engineering project (Defense Acquisition Guidebook (DAG) 2013). Requirements are the expression of the "need" that drives creation of the system. They are, by necessity, established early in the life of the program. The first phase of the DAS - the material solution analysis phase–is fundamentally the process of establishing requirements, validating and verifying them, and creating the concepts and project plans to meet those requirements (see Figure 25.).

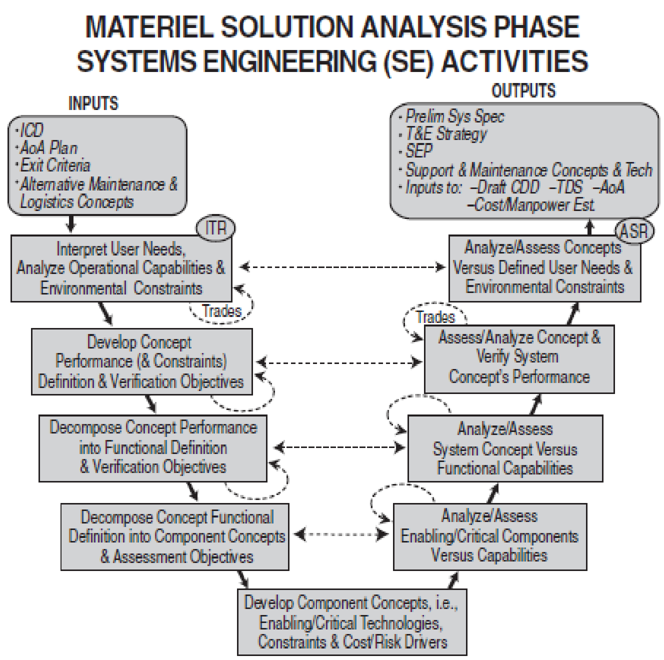


Figure 25. Material Solution Analysis Phase (from DAU 2011, 83)

Blanchard and Fabrycky's *Systems Engineering & Analysis*, a widely used systems engineering textbook, describes requirements this way:

> …(T)rue system requirements need to be well defined and specified, and the traceability of these requirements from the system level downward needs to be visible. In the past, the early "front-end" analysis as applied to many new systems has been minimal. The lack of defining an early "baseline" has resulted in greater individual design efforts downstream. Many of these are not well integrated with other design activities, causing costly modifications later on. (Blanchard and Fabrycky 1998, 24)

Similarly, the National Aeronautics and Space Administration (NASA) *NASA Systems Engineering Handbook* states "…clear and unambiguous requirements will help avoid misunderstandings when developing the overall system and when making major or minor changes" (NASA 2006, 32). The *Defense Acquisition Guidebook* states that "…poorly written requirements can lead to significant problems in the areas of schedule, cost, or performance, and can thus increase program risk" (DAG 2013, 158).

The Defense Acquisition University provides the mandated training for program managers and systems engineers specified by the DAWIA act. One of its foundation courses is "Systems Engineering Fundamentals" which contains the following attributes of a good requirement:

> It must be complete and contain all mission profiles, operational and maintenance concepts, utilization environments and constraints…
>
> Requirements analysis should result in a clear understanding of:
>
> Functions: what the system has to do,
>
> Performance: How well the function has to be performed,
>
> Interfaces: Environment in which the system will perform. (DAU 2001, 36–37)

Establishing clear and comprehensive requirements fulfills two purposes in a project. First, it ensures that the project will meet its intended purpose and therefore that the project is satisfying the "big picture." Although this seems self-evident, more than one project has been initiated because of "…personal interest or political whim, without first having adequately defined the requirement" (Blanchard and Fabrycky 1998, 46). Second, requirements drive the functional analysis, which ultimately produces the system conceptual design. The conceptual design, in turn, feeds the creation of the detailed design and the eventual configuration to be fielded. Hence it is essential that the requirements be complete so that the system designers account for every system need without having to reallocate or redesign, both costly and time-consuming activities.

2. Integration

Integration is another essential element of systems engineering. Integration of system elements is what produces the benefit of a system (Madni 2012). In many discussions of systems engineering, integration is approached as one of the many required processes on the "upward" portion of the SE "V" model (shown in Figure 26.) (Blanchard and Fabrycky 1998).

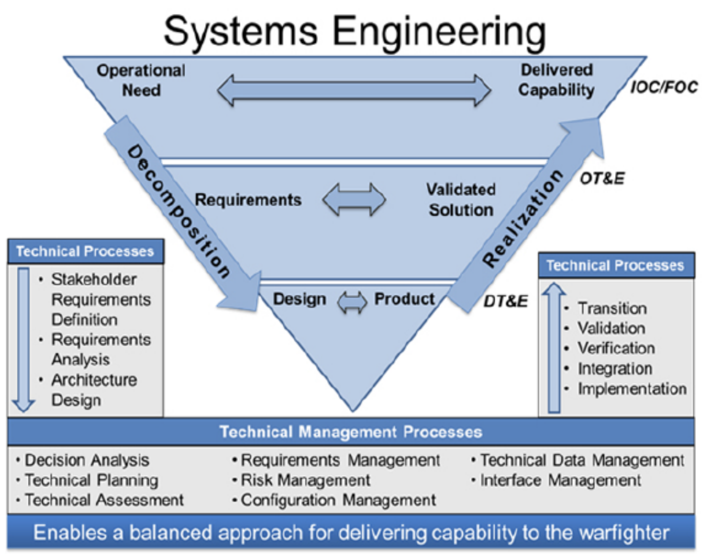


Figure 26. V Model of Systems Engineering (from DAG 2013)

In this "process" focused point of view, system integration (SI) can be accomplished using a variety of techniques. All of these techniques stem from the traditional "waterfall" model of SE (precursor to the "V"); several were developed in response to the ever-increasing complexity (and consequently more difficult integration) of modern systems (Madni 2012). Methods of integration include the layered integration, "plug-and-play" integration, horizontal integration, and build integration (Madni 2012).

While certainly a valuable benefit of the SE process, if one views SE as a series of processes to be accomplished, integration is much more fundamental than merely a process to ensure system components are compatible.

Professors Gary Langford and Derek Hitchins have presented complimentary views of the critical importance of integration to the success of any SE project. Hitchins approaches integration from his "macro" level discussions of systems thinking and the benefits of SE design "synthesis" versus the traditional "reductionist" engineering approach (Hitchins 2013). Langford, on the other hand, presents a "micro" level view of integration and creates a framework for conducting integration and analysis while also emphasizing the absolute centrality of integration to engineering success (Langford 2012).

Hitchins' views on systems engineering and integration can be found in his several books and numerous essays published at his website "Systems World" (www.hitchins.net). His "First Principle of Systems" and "Corollary to the First Principle" are particularly useful: *The properties, capabilities, and behavior of a system derive from its parts, from interactions between those parts, and from interactions with other systems. Altering the properties, capabilities, and behavior of any of the parts, or any of their interactions, affects other parts, the whole system, and interacting systems* (Hitchins 2013). That definition captures the importance of understanding that a system can produce results greater than any of its constituent parts. He uses the term "emergence" to denote this phenomenon and emphasizes that emergence is the key to understanding the value to be gained by pursuing systems engineering principles.

A naval anti-ship cruise missile (ASCM) defense system is a good example of emergence resulting from integration. Radars and other sensors cannot defend the ship. Electronic warfare may defeat some threats but not others; some threats may or may not be susceptible to decoys; and defensive weapons (guns and missiles) may or may not defeat still other threats. But a combination of all of those systems provides the defending ship a higher probability of defeating enemy missiles. Hence, the process that creates emergence (integration) has to be the centerpiece of any development effort.

Langford's recent text *Engineering Systems Integration: Theory, Metrics, and Methods* presents an integration framework that is abstract enough to be applied to any system regardless of nature or complexity (Langford 2012). It considers object integration in terms of the exchange of energy, matter, material wealth, and information (EMMI) as influenced by various boundary conditions - physical, functional, and behavioral. Langford also proposes a list of seven integration principles, gathered from numerous case studies, that "…can help guide decisions" concerning the conduct of an engineering project (Langford 2012, 10). The principles are listed in Appendix A; their applicability to DDG-1000 missile integration will be discussed in Chapter V.

Integration is not easy, and it is not a single well-defined process. Instead, it is often practiced in an ad-hoc manner or in accordance with the opinions of various program managers or engineers (Madni 2012, 3). However, Langford and Hitchins make compelling arguments that integration is the most important part of system development because it is the process that produces emergence. Chapter V will assess integration for DDG-1000 from this viewpoint.

3. Management and Organization

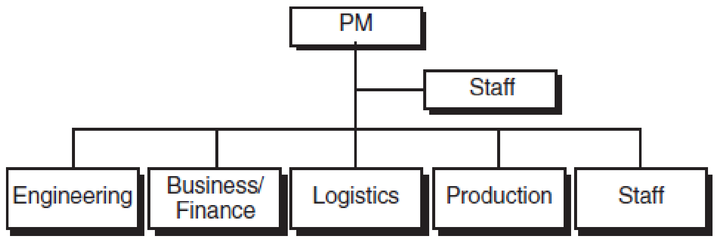
The practice of project management has long been associated with systems engineering and is critical to the eventual success of any engineering effort (Blanchard and Fabrycky 1998; DAU 2001). Just as a well-organized effort will fail without quality engineering, quality engineering alone will not guarantee project success. Indeed, one can reasonably argue that successful engineering is a byproduct of successful management.

What does engineering management entail? At a minimum, management connotes planning, staffing, monitoring and controlling the design, development, testing, and production of a system (Blanchard and Fabrycky 1998). It therefore covers the initial problem analysis and customer requirements, resulting in analysis of alternatives and recommended solutions. It includes the creation of a detailed work breakdown structure (WBS) that will inform budget estimates. It also includes completion of functional flowdown analysis, creation of derived requirements, establishment of technical reviews and test activities, and creation of a mechanism to review design changes and resolve technical problems. Lastly, in includes the preparation of key program documents that capture the items listed. These key documents include an integrated master schedule (IMS), a systems engineering management plan (SEMP), the WBS, and a test and evaluation master plan (TEMP).

The elements of management described entail the organization and activities that must be conducted by the designer/producer of the system in question. In the Department of Defense, however, the purview of managing an acquisition project is much greater. As described in earlier sections on the DAS and the acquisition environment, the project manager must contend with a budgeting process in which his or her project is likely one small piece of a much larger puzzle. The manager must also contend with possible requirement changes and oversight activities that increase the demand on project resources. Lastly, elements of design, test and support for the system being designed are not under the control of the project manager. Thus, the project becomes dependent on other organizations with their own schedule, budget, and performance constraints.

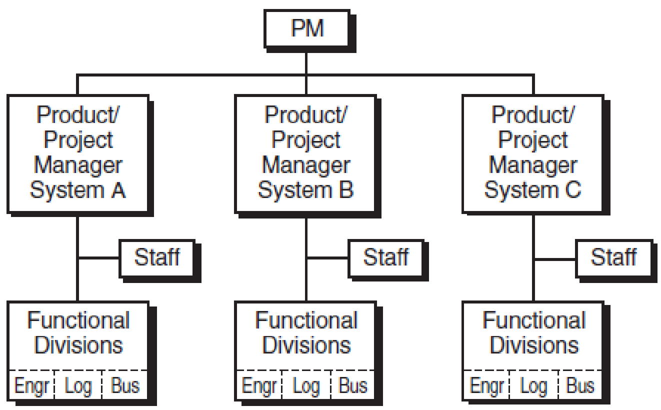
The DOD initiated the concept of *Integrated Product and Process Development* (IPPD) in the early 1990s in order to foster the communication and teamwork necessary to produce a successful project in the acquisition environment (Blanchard and Fabrycky 1998, 634). A central element to IPPD is the creation and use of Integrated Product Teams (IPTs) to manage the interaction of program functions (logistics, production, etc.) with the personnel/organizations that will carry out the function (contractors, DOD test organizations, etc.). Figure 27 shows a traditional program structure, a purely functional structure, and a matrix structure utilizing IPTs.

“Traditional” or Functional Structure



Note: Functional divisions shown are notional.

“Pure” Product Structure



Note: Functional divisions shown are notional.

LEGEND:
Engr—Engineering Log—Logistics Bus—Business

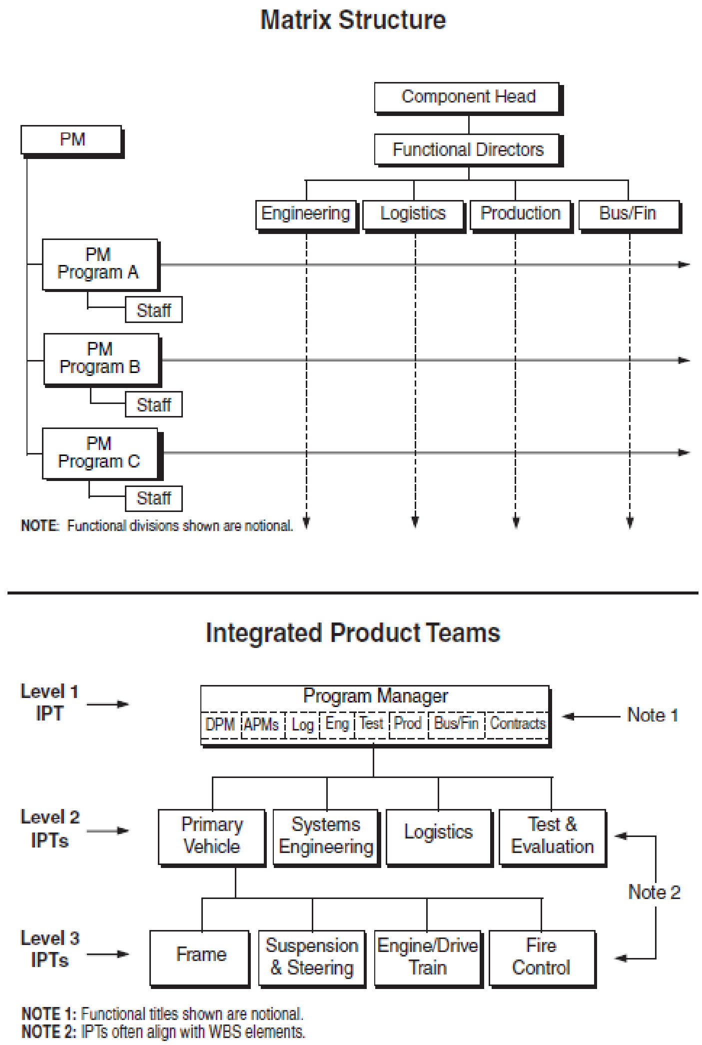


Figure 27. Program Organization Examples (from DAU 2011, 56)

The IPPD/IPT construct is a multi-disciplinary task approach and as such it is extremely dependent on clear lines of communication to function efficiently (Blanchard and Fabrycky 1998, 628). Stating a need for good communication in a large and complex organization is something of a truism; however personal experience has shown that there are still many occasions in which one element of a program was unaware of important developments elsewhere in the project. The IPTs must also be empowered to make decisions related to their functional area and ensure that the ramifications of such decisions were considered beforehand.

A matrix organization as shown will inevitably encounter issues that will have to be resolved at a higher level. In the end, the responsible program manager (PM) must make the difficult decisions. However, analysis of the matrix organization and the DAS show that the PM will often not have the final say, and may have to defer to a higher level authority or a component head for a decision in a certain area. The implications of this organization for DDG-1000 will be examined in Chapter V.

D. SUMMARY

Defense acquisition is a complex process. The DOD has made substantial efforts to implement systems engineering and the life cycle viewpoint into the acquisition process. Congress has established professional education and certification requirements to emphasize the importance of SE in the DOD.

Successful SE must include early establishment of quality requirements for the system. Integration activities produce the emergent behavior that gives the system its value, therefore integration must also be emphasized from the start of the program. The DOD has implemented the IPPD/IPT model into program management in order to improve communication and coordination between the multiple disciplines involved in developing a system, including various design and engineering areas, logistics planning, maintenance planning, in-service support, and so on.

Having discussed the pertinent aspects of the defense acquisition process and the key systems engineering principles inherent in all successful programs, we will now turn our attention to analysis of the DDG-1000 program with respect to requirements, integration, and organization.

V. ANALYSIS

A. INTRODUCTION

At this point we have developed our understanding of the history and background of the DDG-1000 program including its combat system components. We have also discussed the DOD's standard planning, acquisition and budgeting processes and their efforts to incorporate Systems Engineering where appropriate. Armed with that background, we can analyze the success or failure of DDG-1000 missile integration with respect to the key systems engineering tenets of requirements, integration and organization. The analysis will be further informed by additional illustrations, best practices, and lessons learned from other DOD and commercial industry programs.

B. REQUIREMENTS

Chapter IV gave several statements from a variety of systems engineering authorities on the absolute criticality of clear, comprehensive requirements for a development program. These sources were academic (Blanchard and Fabrycky) and from the DOD (the *Defense Acquisition Guidebook*). There are many other systems engineering textbooks and definitions that similarly echo the importance of clear requirements.

Given the widespread recognition of the importance of "good" requirements, one would believe that the DOD would take great pains to ensure clear and comprehensive requirements were established for all of its programs. Yet poor requirements definition continues to plague the DOD. For example, a 2003 report from the NDIA stated "…requirements definition, development, and management is not applied consistently and effectively…" (NDIA 2003). The report continued: "the Government, for the most part…do not follow their requirements process effectively…there is a serious lack of upfront and continuous requirements development and management, including management of requirements changes" (NDIA 2003).

In 2006, Secretary of the Navy Donald Winter stated "…the Navy needs to do a better job of stabilizing requirements. Scrubbing requirements at the beginning of a program is critical. But we also need to strictly control new requirements in existing programs…" (Winter 2006, 4). One of ODASD-SE's top six priorities for 2013 is to "…support realistic program formulation through the application of development planning and early systems engineering…" and "…identifying early systems engineering gaps and deficiencies…" (ODASD-SE 2013).

A 2010 Air Force Institute of Technology (AFIT) case study analysis of eight major acquisition programs, both successful and unsuccessful, found that inadequate or changing requirements were a major reason for poor performance in every unsuccessful program; conversely, all of the successful programs were found to have clear requirements that were adhered to throughout development (AFIT 2010).

Missile integration for DDG-1000 has three significant potential problem areas in terms of requirements; each concern applies equally to both ESSM and SM:

- Top level requirements for the missile have not been established, creating potential performance risk
- The directive to use legacy system requirements creates technical risk
- Requirements have been changed late in the development process, creating technical and integration risks

Each concern will be discussed individually.

1. Top Level Requirements

Top level missile requirements have never been formally established for the JUWL program (IWS3 2012). **Error! Reference source not found.** shows a simplified diagram of the flow of requirements for DDG-1000 missile integration.

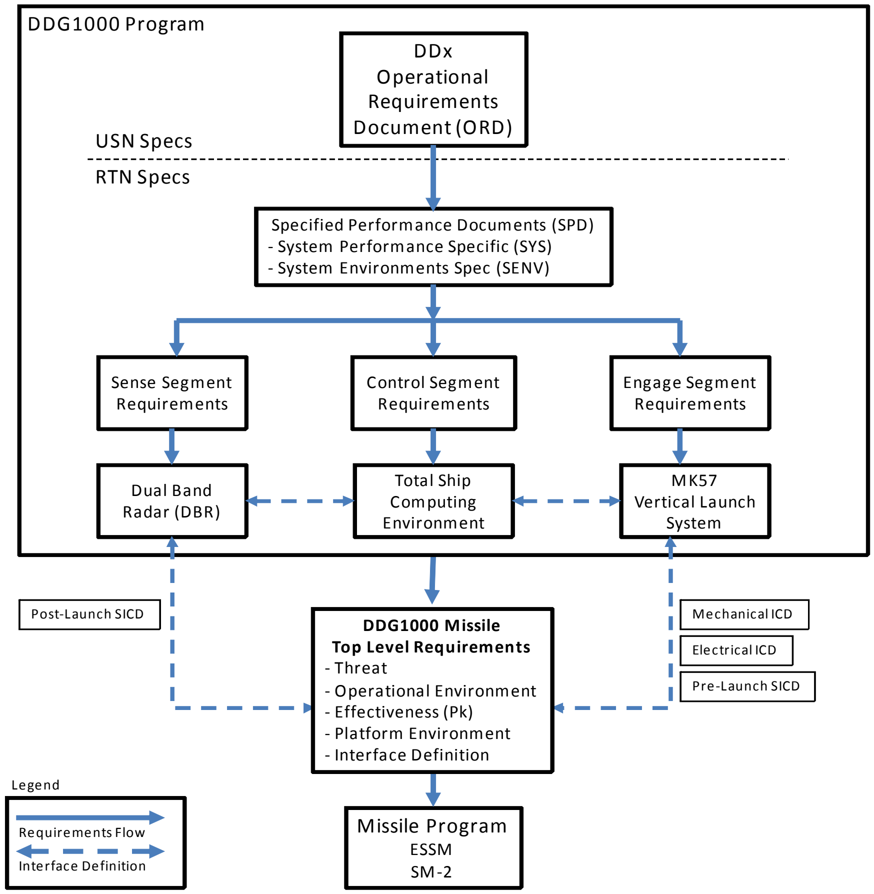


Figure 28. DDG-1000 Requirements Flow (from IWS3 2012)

The DDG-1000 contractor developed a set of system performance documents (SPDs) which included system performance specifications (SYS) and system environment specifications (SENV). The SPDs were then decomposed and allocated to one of the various segments (DBR, for example). The DDG-1000 contractor did not include a missile segment in its analysis. Therefore, the requirements decomposition did not allocate any functional or performance requirements to the missile and did not define any physical or logical interfaces between ship systems and the missile.

Working group meetings between the ship combat system and missile programs were held in 2005 and the gap in requirements flowdown was discussed. A need for pre- and post-launch interface control documents (ICDs) to define data link requirements was agreed to but ship program representatives initially maintained that no missile requirements were needed because the missiles were assumed to perform as they would when launched from an Aegis platform (IWS3 2012). Further discussion of the differences between DDG-1000 and Aegis requirements such as CONOPs, threats, hull environments, and so forth led to an agreement to develop missile requirements. However, the first draft of DDG-1000 missile top level requirements (TLRs) prepared by the combat system program office copied existing Aegis requirements and interface documents. Continued discussions between IWS3 (the JUWL development manager) and IWS11 (the SIPM for DDG-1000 at the time) could not produce an agreement on the content and detail of the missile TLR. The differences continued to center on the suitability of using existing Aegis requirements in the new DDG-1000 environment; the effort was abandoned in 2007. The end result was that all legacy SM and ESSM requirements were considered "good enough" and were to be used as-is; the only requirements changes were those included in the pre- and post-launch ICDs to define data link requirements (IWS3 2012). The SOWs presented to the JUWL prime contractor have reflected this legacy requirement and have thus limited the level of effort in the JUWL program.

0 depicts the flowdown used to achieve the current JUWL prime item development specifications and gaps that still exist in requirements.

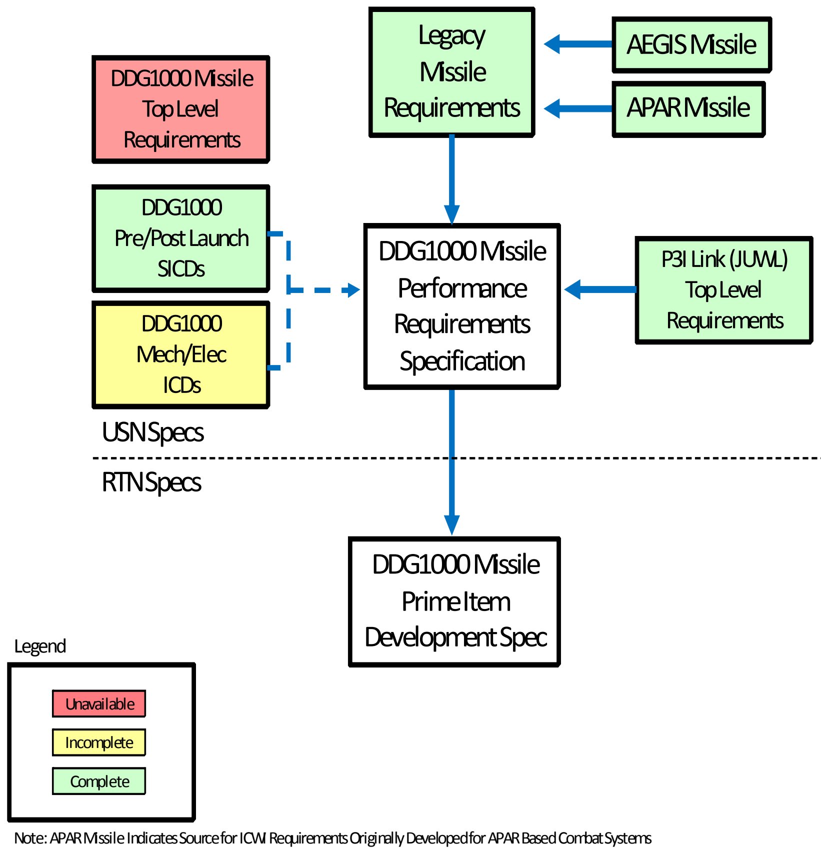


Figure 29. DDG-1000 Requirements Flow (from IWS3 2012)

The gaps in missile TLRs create uncertainty of performance expectations and the Navy's capacity to measure missile performance for DDG-1000. It also results in technical risk, as JUWL development does not include any mechanism for investigating or developing performance improvements in the missiles. The absence of TLRs is clearly in contradiction to the emphasis that SE places on clear requirement definition.

2. Legacy Requirements

Using legacy requirements produces risk in other areas besides mission performance. DDG-1000's mechanical, electrical, and electromagnetic environment *will* be different from that of Aegis ships. Potential for electromagnetic interference (EMI) from other emitters on DDG-1000, as well as potential hazards of electromagnetic radiation to ordnance (HERO) from those emitters, are not addressed in the JUWL program because legacy requirements are in place. Consider that the MFR is an entirely new radar, operating in a new frequency, with new power levels and waveforms. While EMI or HERO issues are not a certainty, they are certainly a potential problem. And more mundane, but no less important, concerns such as the vibration profile of the new hull and the differing proximity of the launchers (and thus missiles) to other hull, mechanical, and electrical (HM&E) systems could result in a situation where a legacy requirement is inadequate or unsafe.

This is not to say projections of DDG-1000 environments are not available or that no consideration has been given to these issues. Projections and models of other systems are available. But the JUWL developer is limited to providing a legacy missile with a new data link, and thus the opportunity to design in response to even the projected environments is lost. As the lead ship in a new class, DDG-1000 will likely undergo a variety of surveys to determine EMI, HERO levels, vibration profiles, near-miss shock levels, and so on. If legacy missile requirements are found to be lacking, the entire DDG-1000 program will face cost and schedule penalties in order to "make up" the difference between legacy needs and DDG-1000 needs.

3. Requirement Changes

DDG-1000 and JUWL have had two significant changes since 2009 that have affected component design. As described in Chapter III, the 2010 program restructuring following the program Nunn-McCurdy breach deleted the VSR from the ship. Some VSR tasks were re-allocated to the MFR, which entailed radar resource management changes and attendant software alterations in the radar and the combat system. These software alterations impact the MFR radar timeline. Timeline changes, in turn, have the potential to impact missile performance. For example, the radar may send fewer guidance commands to a missile in flight, reducing the accuracy of the missile.

These radar timeline changes have to be analyzed, modeled, and then installed into the combat system. Those models must then be made available to the missile designers for assessment of potential changes in the missile. At this time, the combat system contractor has not made a DDG-1000 specific weapon control element (WCE) model available for missile program use (IWS3 2012). Therefore, the JUWL developer has proceeded with the assumption that DDG-1000 will be consistent with the Trilateral Frigate Cooperation (TFC) software that integrated SM with the APAR system (IWS3 2012). It is also unclear if the current radar model adequately reflects any changes resulting from VSR removal. The combat system (C/S) developer has not made a full radar model available to JUWL; they have only provided static radar data as modeled for a cross-section of radar scenarios (IWS3 2012). The entire system will eventually be tested during operational evaluation. Any errors or discrepancies discovered at such a late stage in the program will have major cost or schedule ramifications.

In 2012, the Navy replaced the SM-2 Block IIIB missile with the SM-2 Block IIIA version. This entailed a sizeable design and software change for JUWL as well as changes for the combat system. The internal arrangement of components among the four guidance section plates is different in IIIA missiles and IIIB missiles. Therefore, JUWL designers had to reallocate JUWL components at the circuit card assembly (CCA) level and repeat their design validation and verification activities. The IIIB missile also has different "base" software than the IIIA missile and JUWL designers had to re-perform their software analysis and some software testing before they could import their JUWL specific software into IIIA. The software situation was further complicated by a subsequent decision to include the MU software update into the IIIA build–the JUWL software build will be the first IIIA missile to incorporate MU.

The missile change also impacts the combat system. IIIA follows a different flight path than IIIB during the launch and transition phases of flight. This flight path is predicted by the ship's combat system so that the combat system can accurately direct the radar to "capture" the missile (establish communications). The software producing this prediction is the Missile Trajectory Estimator (MTE). In some cases, the differences between IIIA and IIIB may be significant enough to impact radar performance. At a minimum, the combat system needs to alter and/or analyze the MTE to ensure that it encompasses the boundaries of the IIIA flight profile.

Both of these changes occurred after significant program "run" time. Therefore, both efforts experienced schedule delays and additional expense. Both changes also require coordination between the respective contractors so that system compatibility is maintained. After significant delays (which were attributable to organizational difficulties described later in section D) the combat system contractor has begun performing the necessary analysis of the MTE. However, the C/S contractor has still not provided complete and up-to-date models of the radar or WCE and thus the JUWL developer continues development with added risk. It is unclear if the models do not exist, are not complete, or are not being provided for some other reason.

C. INTEGRATION

Langford and Hitchins make persuasive arguments that integration is most important part of SE development (see Chapter III). Integration produces *emergence*, which is Hitchins' term for the phenomenon in which a system produces faster, expanded, or otherwise "better" system performance than the components of the system could achieve operating independently.

This section will examine DDG-1000 missile integration in terms of Langford's seven principles in integration. Annette Krygiel's 1999 case study entitled *Behind the Wizard's Curtain: An Integration Environment for a System of Systems* also provides a number of key integration insights gleaned from prior large-scale integration projects. We will also discuss other integration case studies that reinforce the critical nature of integration and illustrate the pitfalls of reducing integration to merely something done after "…analysis and design have taken place…" (Hyer et al. 1996, 315).

1. Integration–Langford's Principles

Langford's Seven Principles of Integration, listed in Appendix A, are an early feature in his text *Engineering Systems Integration: Theory, Metrics, and Methods.* They appear before he explains his conceptual construct of integration and serve to remind the reader that:

> Principles of integration extract insular thinking from the quagmire of confusion, help guide decisions based on the sound and the good of a particular situation, and present a logic that creates an air of confidence. In as much as the principles help others justify their actions, the mere fact of discussing and employing principles facilitates decision fitness and decision making throughout an organization (Howard and Matheson

> 1984), reinforces the teamness that inspires success, and provides a top-level perspective that retains purpose, objectivity, and planning prowess. (Langford 2012, 10)

Langford's Seven Principles are the Principles of Alignment, Partitioning, Induction, Limitation, Forethought, Planning, and Loss. While all of Langford's principles apply to any integration activity, this paper will focus on those deemed most relevant to missile integration on DDG-1000.

a. Principle One–Alignment

Langford's alignment principle states that alignment of strategies between the business enterprise, key stakeholders, and the project results in better outcomes for product development. He states "…knowing the needs of the project and how those needs are supported by the business enterprise and the key stakeholders is important in keeping high-level visibility with the decision makers...systems engineers place great importance on working with stakeholders to determine requirements, verify that the work accomplished satisfies the requirements, and deliver to satisfy the user requirements" (Langford 2012, 11). For the DDG-1000 program in general, and missile integration in particular, strategies have not been aligned.

The clearest example of misalignment is the fundamental disagreement concerning the appropriateness of a "use-as-is" decision for missile requirements discussed in Section B. The author believes that a use-as-is requirement is *prima facie* unrealistic; the ship's missile launchers, combat system, and radar are all new development items. If there were no differences involved, then no integration would be needed. However, the SIPM clearly felt that similarities to existing systems (the APAR version of ESSM and SM) warranted the lower cost "use as is" decision; if no significant software or interface problems are uncovered before and during operational testing their opinion will be confirmed. However, history suggests that this will not be the case.

In 1996, the Ariadne 5 rocket lost flight control immediately after launch and was completely destroyed. The root cause was found to be failure to integrate and test two software elements in the rocket's inertial reference system (Madni 2012). In 1997, the

USS Yorktown suffered a complete failure of its "smart ship" system. The system was installed in 1996 as a completely automated way to control the engineering plant; the ship had to be towed to port after the failure. The problem was traced to inadequate testing of data interfaces; a zero inadvertently entered into a data field caused a "divide-by-zero" error which crashed the entire computer network (Madni 2012). The Airbus A320, an enormous commercial aircraft project, was delayed by over two years (at a cost of $6 billion) because of a simple semantic error on a mechanical description document between a German subcontractor delivering wiring harnesses and the French factory constructing the aircraft (Madni 2012). Other high profile examples can be found in NASA's Hubble Space Telescope program; the Air Force's Theatre Battle Management Core System (TBMCS); the F-111 and A-10 aircraft programs; and the Global Hawk UAV program (AFIT 2010).

Misalignment can also stem from organizational differences and the associated differences in contract content and schedules. The responsibilities for producing DDG-1000 and its combat system are spread over three program offices and three prime contractors; coordination of effort is thus more difficult. Further discussion of organizational issues appears later in Section D.

b. Principle Four–Limitation

Langford's fourth principle states that integration can only be successful to the same degree that the architecture is successful in capturing stakeholder requirements. DDG-1000 missile integration faces a significant problem because engineers and designers are developing systems to integrate with other systems that are likewise in development. Hence interfaces, standards, and performance are all subject to change. This makes a development program more difficult–although DDG-1000 is certainly not unique in this respect. The absence of clear requirements discussed in Section B also falls under this principle, as an architecture cannot be truly developed until a firm set of requirements is in place for the architecture to meet.

However, a second key point Langford makes with the principle of limitation is the importance of the concept of operations (CONOP) in guiding architecture developers and component designers. The CONOP is a critical document that must be kept current. In the absence of other, detailed specifications, it provides designers a frame of reference to plan their activities and is an invaluable tool for a design team (Langford 2012). The DDG-1000 AW CONOP has not been updated to reflect significant program changes. In particular, it does not reflect the removal of the VSR and the change from SM2 Block III-B to III-A. Given the absence of specific requirements, the out-of-date CONOP further constrains the development team because they do not have a reference document to refer to when conducting trade studies or planning for testing.

c. Principle Five-Forethought

Langford states that integration is a primary, key activity–not an afterthought considered as a result of development. The following quotes are illustrative of his view on the subject:

> Integration is a daily focus, with periodic updates to the integration plan. Integration is an explicit goal of acquisition… (Langford 2012, 19)
>
> …planning for integration alleviates problems that surface during integration (Langford 2012, 20).
>
> …often requirements are left unstated…at best, this technique of building systems is a guess at building objects so that performances are met…this guess-and-try again approach to integration is time-consuming and dollar-expensive. (Langford 2012, 20)

DDG-1000 missile integration has fallen squarely into the trap of the "guess-and-try again" paradigm.

2. Integration–Krygiel's "Best Practices"

A 1999 DOD case study report entitled *Behind the Wizard's Curtain: An Integration Environment for a System of Systems* examined large scale system of systems integration in two projects: The Army's Task Force XXI (TF XXI) and the Defense Mapping Agency's (DMA) Digital Production System (DPS). The DPS was intended to produce an end-to-end digital production system for all of the DMA's mapping, charting and geodesy (MC&G) products (Krygiel 1999). TF XXI was an Army project born out of

Army Chief of Staff Gordon Sullivan's efforts to fundamentally re-constitute the Army after the end of the Cold War. Sullivan believed the down-sized, post-Cold War Army would need to be expeditionary in nature and would need "…fundamental changes in every aspect of the Army, including structure, doctrine, capabilities, training, and tactics" (Krygiel 1999, 72). Such an expeditionary force would depend on a "digitized battlefield" with cutting edge information technology (IT) and command and control (C2) systems. TF XXI was tasked with conceptualizing, testing, and selecting the C2 and IT systems for the "Army after next" (Krygiel 1999, 74).

The case study produced nine integration recommendations, similar to Langford's seven principles. In fact, some of the recommendations are nearly identical. The most relevant recommendations will be discussed here; the entire list can be found in Appendix B.

a. Lesson 1

Lesson 1 states that some activities must occur before integration, including developing the system architecture, developing and testing the system constituents, and developing and testing all interfaces. Annette Krygiel, the author of the study, makes this observation when discussing "pre-integration" activities:

> The promise of plug-and-play is a seductive one…(t)his lesson serves to remind that verifying the individual constituent systems and interfaces and certifying them for architectural compliance are not activities which conclude the integration process but rather are necessary to begin it. The lesson is applicable to a SOS which is a "new start" or one which incorporates many legacy systems. (Krygiel 1999, 148)

While there is a great deal of debate regarding the appropriateness of the term "System of Systems" in the greater SE community (see, for instance, Hitchins [2012] or Stuckenbruck [2008]), there is no doubt that the "use as is" requirements of the ESSM and SM missile have resulted in a false belief that integration is something that is done to conclude a project. Krygiel (like Langford) found that integration success is greatly improved by emphasizing integration needs early; failing to do so increases risk.

b. Lesson 4

Lesson 4 states "…To integrate all the systems of a SoS, plan for substantial difficulties and significant time and resources" (Krygiel 1999, 158). The report goes on:

> This lesson rejects outright the assumption of plug-and-play, even while presupposing that the appropriate testing of individual systems and their interfaces has occurred. It provides a counter-assumption for planning purposes based on current experience—that the integration of a SOS is a strenuous undertaking. (Krygiel 1999, 159)

This is a clear rejection of what are often termed "overly ambitious schedules." Even if appropriate pre-integration activities have occurred, managers should still expect to expend significant time and resources on performing a thorough integration effort. The resource needs increase with the complexity of the systems to be integrated.

The JUWL integration plan is very ambitious. The current schedule allows each missile variant one three-to-four month period for "ground-based" integration with the C/S prior to at-sea flight testing. At this time, the ground integration tests will be performed with a version of the C/S software that will be different than the flight test version. Successful flight tests will therefore depend a great deal on the type and extent of the differences in the final two DDG-1000 C/S software versions and the base APAR software that has directed JUWL development. As discussed above, the lack of radar and WCE models has forced the JUWL developers to use the original APAR/ICWI software as a basis for modeling and component testing.

Furthermore, the testing plan reflects an intention to "leverage" the results of ESSM (the first missile to conduct integration testing) into the SM integration activity. The essentially means that SM will not conduct the same "suite" of integration tests and activities that ESSM does on the assumption that what works for ESSM, given the common data link, will work for SM. While this is certainly possible, it does not allow for the resolution of any problems that may be encountered. In addition, the CVN-78 program is planning on "leveraging" from DDG-1000's ESSM integration, despite the fact that the DBR and C/S implemented on CVN-78 will not be the same as that implemented on DDG-1000. The compressed, aggressive integration schedule must be considered a risk in light of Krygiel's Lesson 4.

c. Lesson 7

Lesson 7 contains the following recommendations:

> Certain common processes and common infrastructure in the integration environment are essential to manage a SOS integration successfully. These include the following…an Engineering Board with responsibility and authority for identification and resolution of SOS issues and discrepancies, including the assignment of responsibility for correction…establishment of processes (and the automated means) for identification of SOS issues and discrepancies, their disposition, tracking, and resolution, under the management of the Engineering Board…a formal build, verification, and re-integration process for changes…. (Krygiel 1999, 167–168)

The lack of a consistent, effective mechanism to resolve technical issues between the C/S and missile programs has hindered the JUWL effort. The missile program has recognized many of the potential technical and integration risks described in this thesis (IWS3 2012). A missile integration working group (MIWG) was established to analyze technical problems and assign actions to resolve those problems. The MIWG was disbanded and restarted several times over the course of the program; the last disbanding occurred after the 2010 restructuring of the entire DDG-1000 program, and the subsequent deletion of integration funding. This was a particularly unfortunate time to eliminate the group as other changes from the restructuring, deletion of VSR, for example, drove changes into the combat system.

Even if the MIWG and its adjunct group, the Missile Integration Change Control Board or MICCB, had remained in operation from 2010–2012, the "use-as-is" requirement decision resulted in statements of work that precluded design changes in legacy hardware. Such work was deemed "out of scope" in contractual terms. Therefore, even if an integration problem is identified, such as the MTE issue described earlier, it is difficult for the program offices to enable the contractors to perform the necessary analysis and/or corrective action. These delays only exacerbate the potential for last minute "show stoppers" to cause significant cost increases and schedule delays for DDG-1000.

3. Integration–Other Best Practices

Johns Hopkins University's Advanced Physics Laboratory (JHU APL) assisted the NATO Sea Sparrow Program Office (NSPO) with planning and conducting the integration of ESSM with the varying combat systems and ships of the Sea Sparrow consortium nations (Hyer et al. 1996). The development effort began in the mid-1990s and ESSM began operational testing in 2002.

One of the key integration steps taken early in the ESSM development effort was the establishment of a Systems Integration IPT. The SI IPT interfaced directly with the ESSM Integration IPT (see Figure 30.). The ESSM Integration IPT was part of the prime contractor's IPPD structure and oversaw numerous component IPTs as they performed their design activities–engineering analyses, trade studies, and so on. The SI IPT provided a forum for the various consortium navies to bring forward various issues directly to the design team. This was a critical step, as ESSM was to be operable with six different combat systems on 13 different classes of warship while also maintaining some capacity for future expansions (Hyer et al. 1996, 319).

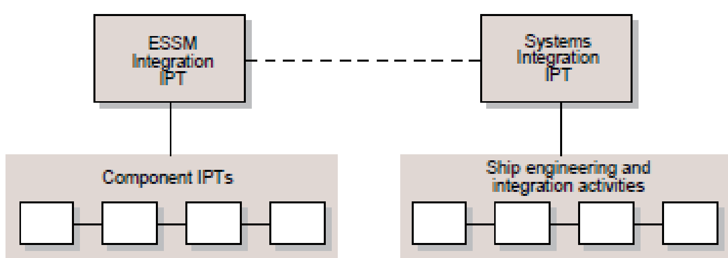


Figure 30. ESSM Development IPTs (from Hyer et al. 1996, 321)

The arrangement was intended to allow the various nations an opportunity to pursue their individual C/S needs and also allowed the program to identify and develop common interfaces where possible. It also gave the opportunity to influence design in order to mitigate identified configuration issues (Hyer et al. 1996). This type of arrangement, as noted in Section (2), has been lacking for the DDG-1000 missile integration effort.

The Defense Acquisition Guidebook discussion of SE (found in Chapter IV, emphasis added) states the following:

> A system ***should not be acquired in isolation from other systems with which it associates in the operational environment***…to that end, the Program Manager and Systems Engineer should define intersystem interfaces…the Program Manager and Systems Engineer should also actively pursue Memoranda of Agreement or Memoranda of Understanding (MOA/MOU) with companion programs regarding interfaces, data exchanges, and advance notices of changes, interdependencies and schedule (timing) that may affect either program. These agreements are… a means of mitigating the inherent risk in planning to deliver a capability to an anticipated future technical baseline when there is uncertainty that the other programs are able to maintain schedule and have adequate resources to deploy the capabilities as planned. (DAG 2013, 156)

The DDG-1000 missile integration effort does have MOAs in place, but as described earlier, coordination has not always been timely or productive.

D. ORGANIZATION

Integration of large, complex systems is not easy. Establishing the correct engineering organization is critical for success (Stuckenbruck 2008). Many of the concerns that DDG-1000 missile development has faced are not unique–all major acquisition programs face the same challenges. The DOD routinely institutes new or improved processes or organizational structures in an attempt to improve the outcomes of the DAS.

Weapon system acquisition for the Navy had traditionally been tied to platform development. Once the weapon system was operational, the program office shifted into a primarily sustainment mode, with the possibility of additional development work to field weapon improvements. In 2002, PEO IWS was organized for the specific purpose of consolidating Navy combat system acquisition from a vertical, platform-centric approach to a horizontal, functional approach (Mink 2006). The reorganization was in concert with a new open architecture (OA) acquisition approach for combat systems. The new OA philosophy was a "…multifaceted business and technical strategy for acquiring and maintaining National Security Systems (NSS) as interoperable systems that adopt and exploit open-system design principles and architecture" (Emery 2010, 2). The express goal of the reorganization was to reduce costs (Kime 2004; Syring 2012). The cost savings were to be realized from "cross program efficiencies…multi-year procurement potential…challenging fixed and support costs…(and) maximizing leverage across product lines and programs" (Deegan 2012).

Certain offices in PEO IWS are specifically established as Systems Integration Program Managers (SIPM); Figure 31 shows the weapon acquisition process as envisioned during the reorganization of PEO.

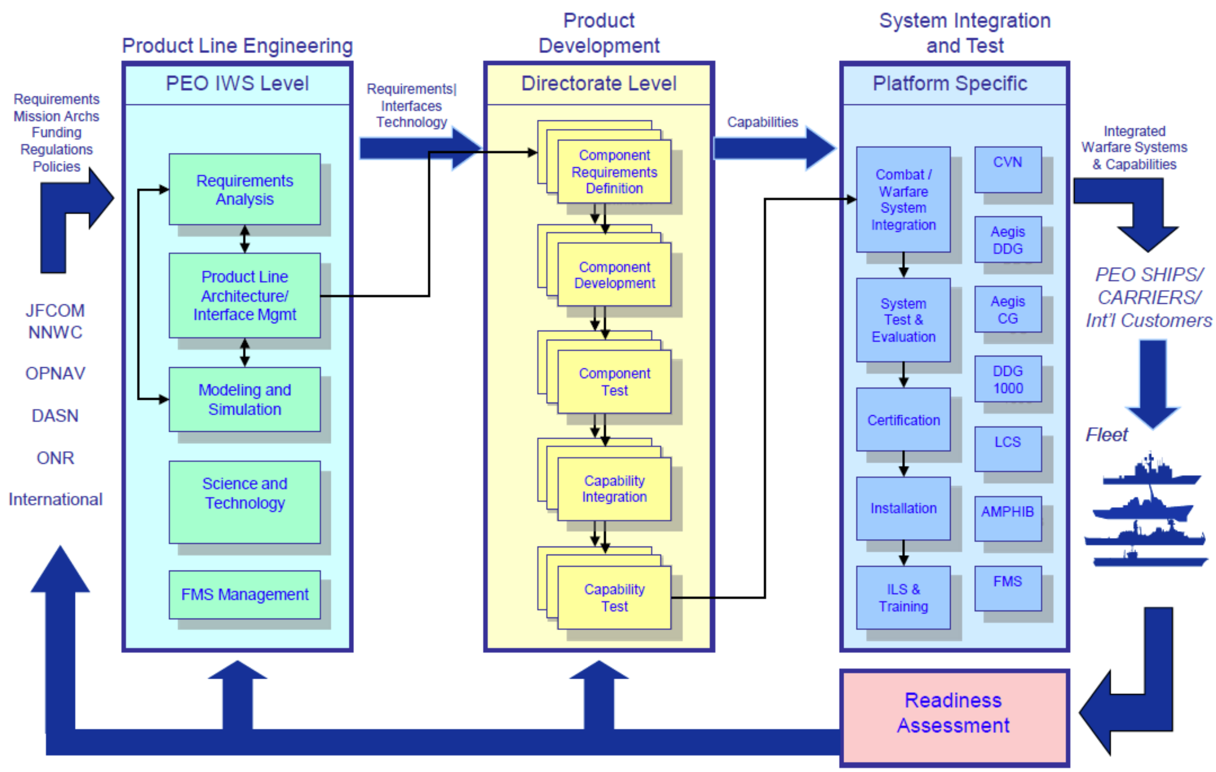


Figure 31. PEO IWS Notional Acquisition (from Emery 2010)

Several challenges remain for PEO IWS to achieve the type of consolidated control that Assistant Secretary of the Navy for Research, Development, and Acquisitions (ASN RDA) John Young envisioned at the time PEO IWS was created.

First, and perhaps most important, is the fact that funding streams for various projects (including JUWL) are not managed by PEO IWS. This clearly contradicts the intended process shown in Figure 31. Shipbuilding and Conversion, Navy (SCN) funds pay for the development and construction of all naval vessels; such funds are controlled by the ship program office. JUWL (for example) is a development effort tied to a new class of ship; hence SCN funds pay for program activities. This divide between weapon development and funding inhibits the stated IWS goal of reducing the number of baselines in the weapons inventory and creation of over-arching warfare systems–because IWS cannot pay for them directly (Mink 2006). "Legacy" weapon programs are funded via Other Procurement, Navy (OPN) allocations and do not face such challenges.

The inconsistency in funding is indicative of a more general problem concerning authority, responsibility, and the delineation of roles and responsibilities. Different program managers (PEO Ships, PEO IWS, PEO Carriers, and so on) will clearly have different opinions on programmatic risk and different priorities in program execution. Memorandums of Agreement (MOAs) are often used to define roles and responsibilities, but they are by no means a guarantee of success. For example, ship program managers (SPM) often maintain configuration control for any system being installed on the hull, whether it is combat system-related or not (Mink 2006). Some SPMs moved their combat system related staff to the IWS equivalent office, while others did not. Therefore, some SE tasks and organizations are undoubtedly duplicated at great cost. Failed coordination of other activities can have operational consequences:

> An example of uncoordinated ECPs can be seen when coordinating changes to the Warfare System Interface Diagrams (WSID). They depict all warfare system elements and their interconnectivities for each ship and are used to maintain ship warfare system configurations. In the past, requested WSID changes to aircraft carriers, amphibious, auxiliary, Coast Guard, and land-based test sites (LBTS) have often bypassed the PEO IWS Warfare System Engineers responsible for system engineering coordination for these platforms. These uncoordinated changes, when implemented aboard ships, have resulted in warfare systems having impaired operability. Fixing these unexpected integration problems consumes resources that are often unbudgeted…. (Mink 2006)

IWS 9 has the role of System Integration Program Manager (SIPM) for surface weapons and is "dual-hatted" as the program manager for the development of the MFR. The other IWS office codes involved in DDG-1000 missile development (3A) and eventually missile production (3A and 3D) can be seen as fulfilling subcontractor roles to IWS 9 and PMS 500. As stated, some IWS program managers (cast in the role of "subcontractors" to the overarching ship program manager) do not control their funding. General communications between the various offices and their respective contractors are hampered by the multitude of SOWs, funding available to support technical exchanges, and general procedural cumbersomeness. Methods to address engineering change proposals (ECPs) vary from one program to another and can be repetitive, costly, or more seriously, not well established.

As with many organizational improvements and "comprehensive" changes, failure to enact the entire bundle of improvements can result in less improvement than expected. In some cases, incomplete changes could produce worse results than the original configuration. Critics of the establishment of PEO IWS highlighted concerns over disrupting successful programs, the size and complexity of the effort, and an over-stretched span of control for IWS managers (Kime 2004). The last eleven years may have proven the critics to be at least partially correct.

While the JUWL effort for DDG-1000 does not use the Lead Systems Integrator (LSI) concept, similarities do exist between the LSI concept and the current matrix organization of PEO IWS. The matrix organization of PEO IWS resembles the LSI concept in the fact that the lead systems integrator is not the same organization responsible for managing all of the constituent systems to be integrated. The organizational structure for DDG-1000 integration encounters many of the same problems that LSI programs encountered which are described below.

In essence, the LSI concept involves hiring a firm to conduct the system development and program management activities that the government traditionally performs (Gully 2003). It was first employed in the Army's Future Combat System (FCS) program. The FCS was intended to develop a SoS that would meet the Army's modernization needs well into the 21st century. The original FCS SoS architecture consisted of nine manned ground vehicles, four unmanned aerial vehicles, four unmanned ground vehicles, and numerous unmanned ground sensors; all "networked" together by multiple communications and C4ISR systems (Gully 2003).

The Army selected the LSI approach for the FCS because it felt it did not have the expertise to manage the development and integration of over 20 separate supporting programs. The Army also felt it did not have the time to develop such an organization because of FCS's aggressive timeline and the cumbersome federal personnel system (Flood and Richard 2006). Hence the Army contracted an industry team to perform the LSI role. Boeing and Science Applications International Corporation (SAIC) were selected as the LSI.

The LSI arrangement, while theoretically sound, encountered immediate problems. Most problems can be grouped into two categories: "cultural" and "procedural." The cultural problems arose from the new duties and responsibilities assigned to participants in the system. Government program personnel, used to authority and responsibility, were relegated to oversight tasks. This often led to adversarial or strained relations when the LSI made programmatic decisions counter to the program office's desires. The LSI, in turn, felt that the Army was not prioritizing the FCS in comparison to other programs and also felt that many in the Army opposed the entire network-centric concept. This doubtless led the LSI to discount the Army's opinions on the many issues raised in the early stages of concept development (Flood and Richard 2006).

Relations between the LSI and the various subcontractors were also strained, as many "subs" believed the LSI was ignoring their concerns or otherwise maneuvering to win future production and development contracts for architecture components under consideration (Flood and Richard 2006, 364). Congress balked at the loss of monetary control over FCS–the LSI effort was a single program element (PE) in the Army budget and thus the LSI had much greater control over funding than a traditional program manager. Congress was also concerned with the incentive fee structure of the contract; various reports pointed out that the LSI could receive some or all of its substantial incentive fees even if the Army never took delivery of a single FCS component (GAO 2007).

Procedural problems also haunted the FCS program. Program participants in both industry and government universally stated that the FCS contracts were not specific enough to give the government a means to enforce its oversight role. There were no mechanisms in place to resolve requirements disagreements, for example, and the LSI made these programmatic decisions by default. The processes in place for integration and lower-level requirement coordination were slow and cumbersome. Many subcontractors and government personnel felt that their concerns were "buried" by the LSI, or at the least were not heard at the appropriate level (Flood and Richard 2006, 367). Indeed, an industry "whistle blower" resorted to posting video explanations of his concerns with the program on the Internet when he felt he could not gain traction with anyone in the LSI hierarchy (Gansler 2009).

The FCS was the target of considerable Congressional scrutiny and was re-organized three separate times before finally being cancelled in 2009; the "subsystems" that had not been cancelled were relegated to various other program offices.

The FCS is not the only example of the LSI concept "gone wrong." The Coast Guard's "Deepwater" program was a similar, large scale development designed to produce a networked SoS of cutters, patrol boats, aircraft, and unmanned vehicles. The LSI in this case was a joint effort of Lockheed Martin and Northrop Grumman. The first contract was awarded in 2002. By 2007, the Coast Guard took over the LSI role because of perceived poor performance, delays, and cost overruns. In subsequent years, significant components of the original SoS were cancelled, including the various unmanned aerial vehicles and several of the proposed surface ships and craft. The Deepwater project, much like FCS, was finally cancelled in 2012 with remaining development assigned to specific program offices (Lipowicz 2013).

The FCS and Deepwater programs were so poorly regarded that in 2008 Congress passed legislation prohibiting any future acquisition program from utilizing the LSI approach (Gansler 2009).

The funding and communication difficulties experienced by PEO IWS when working with other program executive offices is similar to those experienced by FCS and Deepwater. PEO IWS features an internal matrix organization that is specifically designed, like any matrix organization, to balance the needs between integration and specialization (Stuckenbruck 2008, 211). However, implementing an effective matrix requires consistent effort towards fostering effective management interfaces and a great deal of planning and effort (Linnebuck 1988). Unfortunately, PEO IWS does not merely have to manage its internal organization; it must also interface with program elements beyond its control.

E. SUMMARY

Missile integration for DDG-1000 is a seemingly straightforward technical effort. However, in the context of systems engineering, "straightforward" does not necessarily mean "easy." For DDG-1000, missile integration has been challenging because of requirement, integration, and organizational issues.

Major elements of the program did not agree on the importance of establishing new top level requirements for DDG-1000's intended missiles. Instead the decision was made to use legacy missile requirements for every aspect of the missile except the new data link. This introduced substantial risk because the unspecified operational needs and unknown hull environments of DDG-1000 may not be satisfied by legacy missile specifications.

Integration has also been challenging. Despite substantial evidence from prior programs and over-arching guidance from the DOD, integration appears to be an afterthought for many programs, including the missile components of the DDG-1000 program. Each missile variant has approximately three months allotted to conduct all of the integration activities needed with the radar and combat system before the missiles are scheduled for their first test firings. Scheduling initial integration activities so late in a program increases cost and schedule risk because unanticipated problems will be harder to correct. Changing requirements late in the program also increases risk, for similar reasons. The program must also have a robust method for assessing and rectifying technical integration challenges that are identified by designers.

Organization structures can influence both requirement and integration challenges. In the case of PEO IWS, its matrix organization would be ideal for this sort of development effort if it was also funded adequately to perform its integration manager role and had complete control of the development funds dedicated to its programs. Any large scale integration effort faces challenges in communication and coordination; the establishment of a robust “Systems IPT” or engineering change control board is critical to resolving technical issues as they arise.

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VI. FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

A. FINDINGS AND CONCLUSIONS

The strategic situation that gave rise to the early DDG-1000 concept of a land-attack destroyer changed rapidly as the United States reacted to the post-Cold War world. The first reaction to the collapse of the Soviet Union, when combined with the near-simultaneous technological triumph of the First Gulf War, produced the "Revolution in Military Affairs" paradigm. The RMA emphasized technical dominance and the DDG-1000 was deliberately intended to feature "next generation" technology in every aspect of the ship. This was in direct contrast to the Navy's longstanding experience of adding one or two emerging technologies to known hull forms–perhaps best exemplified by the commonality and incremental growth between the FFG-7, DD-963, CG-47, and DDG-51 classes. Ironically, the Navy submarine force had just experienced the perils of inserting too many new technologies (and the concomitant risks and cost) into its next generation platform (the Seawolf class); many of the issues that affected Seawolf are replicated in Zumwalt.

The changing strategic situation resulted in requirement changes and cost growth (as the numbers of intended ships were repeatedly reduced). The most consequential change for missile development was the deletion of the VSR from the ship. This, in turn, drove changes into the MFR–particularly in the areas of radar timeline and, potentially, the concept of operations. The impacts of those changes have yet to be fully identified and tested.

The drive to use existing missiles in DDG-1000 led to a "use as is" decision regarding top-level missile requirements for the ship. Only new requirements for a data link were generated. All other missile requirements (performance, safety, mechanical and electrical interfaces, and so on) remain unchanged from the missiles' Aegis system requirements. The "use as is" decision does not change the fact that the DDG-1000 environment will ***not*** be identical to an Aegis-equipped vessel. DDG-1000 will have a new radar, new combat system, new launcher, new hull form, and new mission–all distinct from legacy Aegis ships. Therefore, the program accepted integration and (ultimately) performance risk by not allowing engineers to identify and address potential technical risks early. These risks were compounded by scheduling a late, aggressive integration and test schedule that counted on "leveraging" successful test results between ESSM and SM. This plan will only work if the initial tests are, indeed, successful.

Organizational obstacles exacerbated funding, requirement and engineering difficulties. All development items for DDG-1000, including the DBR and JUWL, are funded via SCN appropriations. The missile integration program managers do not have control of this funding and are at the mercy of someone else's schedules, contract criteria, and priorities. The 2011 shut-down and re-start of the JUWL development program is a prime example of the consequences of a fractured chain of command and funding process. This situation is precisely what the 2002 reorganization of the PEO structure was intended to rectify–but that intended system has not been fully realized.

Organizational structure complicates integration and engineering cooperation. There has not been a consistent, empowered government decision-making body capable of resolving technical issues identified in the respective programs. Therefore, technical risks are continually "carried forward" instead of being resolved at the earliest possible stage.

In the introduction, two overarching question were raised concerning missile development for the DDG-1000 program. DDG-1000 has yet to be launched and no missiles have been fired from the ship. Therefore, it may be premature to definitively state any lessons learned from failures or successes. However, the thesis has clearly identified risks that were accepted by the program that appear to be unwarranted given prior case studies and systems engineering standards. The following table summarizes those risks and potential impacts to the program.

Table 5. Integration Issues and Consequences

Issue	Potential Consequence
No top level requirements	Failure to meet performance needs; safety risks
Late requirement changes	Costly rework, schedule delays
"Use as is" decision	Late identification of integration problems, inadequate architecture design
Poor organizational construct	Poor engineering change and integration control, slow response to new issues

All of the issues have been catalogued and discussed in academic sources, systems engineering documents, and government publications. The results of the thesis verify the guidelines put forth by Langford, Krygiel, and others. Numerous briefings and studies highlight the recurring themes of inadequate and changing requirements, poor organizational design, and underestimates of integration cost and time requirements. Why DOD programs continue to repeat errors of this type is a question that will continue to face program managers and government executives and deserves continuing examination.

B. RECOMMENDATIONS

The DDG-1000 program in general, and missile integration for DDG-1000 in particular, face numerous challenges that seem to be endemic to the defense acquisition system. All of the issues described in this paper have affected numerous development projects in not only all four services of the DOD, but also in other government projects and even in commercial industry.

Congress, the Executive branch, and the DOD have taken steps to rectify these systemic problems, but the complexity of the systems being acquired and the diverse, interwoven organizations needed to conduct the acquisition process continues to stymie reform efforts. These problems are likely to continue, and possibly worsen, as the DOD likely faces near-stagnant growth or even a reduction in future budgets. Integration is commonly one of the first areas to see funding reduced in a project. Many managers still consider it a “nice to have” or consider integration another name for testing (NDIA 2003).

It is critical that Congress, the president, and the DOD not abandon efforts to improve the acquisition system. The following recommendations, based on the principles and lessons learned described earlier, would help mitigate the issues discussed.

First, the DOD must continue to emphasize and enable the application of systems engineering early in the acquisition cycle. Systems engineering as a discipline is intended to resolve many of the engineering development challenges described in this paper. Clear definition of user needs, thorough examination of alternate means to meet needs, and complete translation of needs into clear requirements are the hallmarks of the early steps of systems engineering. This recommendation is in keeping with Langford’s principle of emphasizing integration activities early. Integration is what provides the benefit of the system, and thus it should be emphasized continuously. The benefits of applying systems engineering early have been highlighted in numerous studies, including the IEEE study described in Chapter IV (Elm and Goldenson 2012).

For JUWL, a critical early decision to use ESSM and SM “as is” (with the exception of the new X-band data link) produced substantial risk that has been carried forward through the program. Such a decision would likely not have been made under scrutiny from a vigorous SE analysis. The missiles are required to interact with a great deal more than just the radar system after launch. They must be compatible with their mechanical and electrical environment. Missile performance must meet the performance requirements explicitly established for the combat system or derived from the CONOP. An SE analysis would also have examined the expected life cycle of the missiles and expected number to be produced, and may have identified the SM-2 Block III-B inventory issue that led to the 2012 decision to change from Block III-B to Block III-A.

Application of systems thinking and the SE process can avoid situations such as the one DDG-1000 now faces. The DOD has acknowledged this fact for over twenty years and has taken significant steps to install systems engineering rigor into weapon acquisition. One avenue of further research suggested by this paper is an examination of *why* such steps have not produced more significant improvements in weapon acquisition outcomes. A quick comparison of the NDIA's top five SE issues from 2003 to 2013 shows consistent themes of poor requirement formulation, poor change control, inadequate user involvement, and late-changing requirements (NDIA 2003; NDIA 2008; NDIA 2013). There is also evidence that acquisition programs do not perform the activities they are directed to implement (Masters 2008, 8). The 2010 QDR described four issues facing the DOD that require "imperative" reforms; one of those areas was acquisition (OSD 2010). The acquisition concerns were further described as:

> First, the requirements for new systems are too often set at the far limit of current technological boundaries…(T)he Department and the nation can no longer afford the quixotic pursuit of high-tech perfection that incurs unacceptable cost and risk. Nor can the Department afford to chase requirements that shift or continue to increase throughout a program's life cycle…
>
> Second, the Pentagon's acquisition workforce has been allowed to atrophy, exacerbating a decline in the critical skills necessary for effective oversight. For example, over the past ten years, the Department's contractual obligations have nearly tripled while our acquisition workforce fell by more than 10 percent…(T)here remains an urgent need for technically trained personnel—cost estimators, systems engineers, and acquisition managers—to conduct effective oversight…
>
> Third, our system of defining requirements and developing capability too often encourages reliance on overly optimistic cost estimates… In order for the Pentagon to produce weapons systems efficiently, it is critical to have budget stability—but it is impossible to attain such stability in DOD's modernization budgets if we continue to underestimate the cost of such systems from the start...(T)here are too many programs under way. We cannot afford everything we might desire; therefore, in the future, the Department must balance capability portfolios to better align with budget constraints and operational needs, based on priorities assigned to warfighter capabilities…(OSD 2010, 76)

These are the same problems identified in a host of previous studies. Why have earlier improvements efforts failed? Identification of underlying issues that are stymying the efforts of OASD-SE and others could contribute to better acquisition performance in the future.

Second, programs must require a thorough systems architecture analysis and requirements flowdown for legacy systems integrated with new systems. This recommendation is an amplification of a portion of the early SE process recommended above. The emphasis is necessary because the use of a legacy system as part of a new system raises additional opportunities for a loss of SE rigor. The requirements flowdown process, by which higher system level requirements are examined and assigned to lower level system components, is a key activity in early systems engineering. It ensures that all requirements are accounted for in the system design (NASA 2007). It also provides an opportunity to examine the adequacy of the requirements. If the requirement does not clearly state the need to be met then the requirement will not be easily assigned to a subsystem. This mismatch indicates a need to revise or rework the requirement (Blanchard and Fabrycky 1998).

As we have discussed, program offices face perennial difficulties in maintaining cost and schedule targets. Incorporation of a legacy system, which in theory was already subjected to a rigorous requirements analysis, gives rise to a temptation to save time and money by not performing a thorough analysis of the legacy system in its new application. Such a thought process is evident when considering the fundamental disagreement between the responsible program offices on the necessity of such requirements for ESSM/SM/JUWL. The disagreement points to a need to develop an informed analysis of the issue.

The systems engineering "method" tells us that requirements must be analyzed and flowed down in *any* development project, even one utilizing existing technology (Langford 2012; Blanchard and Fabrycky 1998). Even if one allows that such an analysis was done for DDG-1000 and JUWL, the analysis did not go far enough into the details of integration. It stopped at a high level and claimed that "use as is" requirements were sufficient.

Previous case studies have highlighted the difficulty of integrating even when such an analysis has been performed—programs must be prepared to find unanticipated integration issues (Krygiel 1999, Langford 2012). Adapting a legacy system for modification and introduction into a new system cannot be an excuse to forego the critical initial steps of systems engineering, even if the program is "leveraging" the benefits of integrating a legacy system. As Krygiel noted in her study, "plug-and-play" can be a seductive notion that all too often fails to deliver on its promises.

On a related note, we should consider the logical implications of using legacy weapons with new sensor systems (or vice versa). Consider that DDG-1000 was clearly intended to produce substantial performance improvements in all warfare areas in comparison to the existing Aegis system. The DBR was intended to track more targets with greater precision, engage more targets simultaneously, and so on. Legacy weapons (SM and ESSM) have performance envelopes traced to their requirements when used with legacy sensors. If we are developing a new sensor to expand our sensor performance envelope, have we done analysis to prove that our legacy weapons have a comparable expansion of their performance margin? In other words, DBR may be a significant improvement from Aegis—but such improvements may not be realized without concurrent weapon advancement. Again, early application of the SE process should answer these questions. Furthermore, we should consider the necessity for deploying a next-generation air defense system on a platform originally intended for a primarily land attack role. Would it have been feasible to deploy DDG-1000 with the Aegis system and save the DBR development for the CG-X? Such a plan would have been in keeping with the Navy's practice of deploying only a few new technologies on each new warfare platform.

Third, place all weapon system development funding under the control of PEO-IWS. The 2003 NAVSEA reorganization of its PEO structure was intended to place all weapon system acquisition in the control of the newly formed PEO IWS organization (Kime 2004; Mink 2006). This has not happened in all cases. The vagaries of the PPBE system, the Congressional budgeting process (and all of its political influences), and various statutes regarding federal outlays all combine to produce a fractured funding system. In the case of JUWL, funding flows from PMS-500, the program office responsible for overall DDG-1000 ship procurement. Tying weapons component development to new ship construction (particularly new class construction) increases the organizational difficulties described in Chapter V. Additional layers of coordination and approval result in increased delays. The responsibility to plan development, budget for development, and execute to that budget should reside with program manager closest to the effort. A corollary to this recommendation is the need to adequately fund and staff the integration manager of the project. The integration manager has the most critical piece of the development effort, and should be the driver of the development effort (even if it must cross program office boundaries). This step would also allow the integration manager to adequately fund the engineering change control board or integration IPT as described by Hyer et al. (2006) and Krygiel (1999). It would also allow the weapon program office to organize the change process to reflect the process used in other weapon programs rather than adopting the hull-centered ShipMain and SPM process (Mink 2006, 37).

The great success of the Aegis weapon system is contributable in great measure to the fact that Admiral Meyer and his staff were the single focus for all aspects of the program—not only sensor, weapon, and doctrine development but also logistics planning, maintenance support, and so on. Evidence of this can be seen in the fact that when portions of the program were removed from this "central" control program performance suffered (LaPointe 2013). The most noticeable effect was worsening material readiness of Aegis combat systems and deteriorating levels of expertise; however Aegis software improvements to support BMD also suffered delays and previously unseen integration issues (Harvey 2012). The acquisition system must reflect the military adage that states that authority must be commensurate with responsibility.

C. FINAL THOUGHTS

All of the recommendations listed above, and many other efforts already underway in the DOD to "fix" the acquisition system, require time and money. Given the fact that budgets will likely shrink or stagnate over the next decade, one could be pessimistic about the chances of success even if we accept the necessity of the corrective actions. Despite the general perception of waste and failure in acquisitions, there have been successful programs in recent years. The Virginia-class submarine and the MRAP program come to mind. It does seem that success has become the exception, however, and the DOD (or perhaps more accurately the nation) cannot maintain the status quo.

Removing the government from the management role (as in the Army's FCS and the Coast Guard's Deepwater project) is not the answer. Instead, emphasis should be placed on fully realizing the many initiatives implemented in the past. For example, if the Navy intends PEO IWS to develop combat systems via an open architecture model that can reduce inefficiencies and improve commonality, it should place all funding for weapon development, sustainment, and improvement under the IWS umbrella. PEO IWS is also a logical home for all technical and risk decisions to be made concerning both new and fielded weapons. This would have removed many of the difficulties faced by the JUWL program, particularly as they relate to integration. The DOD knows it must force systems engineering rigor into the early phases of acquisition–recent emphasis on early technical reviews and the creation of Configuration Steering Boards (CSB) for ACAT I programs affirm this—and those efforts must continue.

The Navy has consolidated authority in other programs. The Navy nuclear power program and the Aegis combat system program have produced robust systems that have performed at a consistently high level for many years. Both of these programs had strong leadership, but they were also given all the tools necessary to meet their goals. Perhaps it is time to establish this consolidated control mentality into all weapons system acquisition programs.

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APPENDIX A. LANGFORD'S SEVEN PRINCIPLES

1. Principle of Alignment

Alignment of strategies for the business enterprise, the key stakeholders, and the project results in better outcomes for product or service development.

2. Principle of Partitioning

Partitioning of objects can create tractable problems to solve if and only if boundary contiguity is achieved.

3. Principle of Induction

Inductive reasoning should guide integration management and recursive thinking.

4. Principle of Limitation

Integration is only as good as architecture captures stakeholder requirements.

5. Principle of Forethought

Integration is a primary, key activity, not an afterthought considered as the result of development.

6. Principle of Planning

Integration planning is predicated on pattern scheduling (lowest impact on budget), network scheduling (determinable impact on budget), and ad hoc scheduling (undetermined impact on budget).

7. Principle of Loss

When two objects are integrated, both objects give up some measure of autonomous behavior.

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APPENDIX B. INTEGRATION LESSONS LEARNED FROM "BEHIND THE WIZARD'S CURTAIN"

Lesson 1

Certain activities should precede a SOS integration. These include:

defining the SOS architecture;

developing and testing the individual system

constituents of the SOS;

developing and testing the interfaces between and among the individual systems of the SOS;

independently certifying compliance with the SOS architecture.

Lesson 2

Use early, incremental, and iterative integration to achieve a SOS.

Lesson 3

The testing strategy for the integration of a SOS requires:

an agreed-to plan and process for testing, based on a risk assessment;

a suite of activities representative of the operational requirements of the mission the SOS supports;

the exercising of a full spectrum of the SOS activities (end-to-end) by operators, using the actual constituent systems of the SOS or at least a core SOS.

Lesson 4

To integrate all the systems of a SOS, plan for substantial difficulties and significant time and resources.

Lesson 5

The use of a single facility with an environment of people, processes, and

Infrastructure substantially facilitates the integration of a SOS from individual systems.

Lesson 6

The process for SOS integration should overtly address the leadership of the integration as follows:

an on-site acquisition leader empowered for the integration of the SOS and an on-site leader empowered for the operational community;

supported by a SOS cadre with sufficient resources and authority;

supported by participants who manage, develop, and operate the constituent systems of the SOS.

Lesson 7

Certain common processes and common infrastructure in the integration environment are essential to manage a SOS integration successfully. These include the following:

an Engineering Board with responsibility and authority for identification and resolution of SOS issues and discrepancies, including the assignment of responsibility for correction;

establishment of processes (and the automated means) for identification of SOS issues and discrepancies, their disposition, tracking, and resolution, under the management of the Engineering Board;

automated support for the tracking and tracing of SOS operational requirements;

configuration management and control of the hardware and software baselines of the systems of the SOS by the integration leadership, supported with:

automated means for identifying and controlling the baselines and subsequent changes;

a formal build, verification, and re-integration process for changes;

a robust communications infrastructure linking the teams internal to the integration environment and their external counterparts;

an office automation environment to support the integration's administrative processes as well as to support interpersonal processing and communications for the participants.

Lesson 8

Certain common processes and infrastructure in the SOS integration environment promote effectiveness and efficiencies. These include:

daily planning and scheduling of resources (people, equipment, facilities) for integration events with contingency plans and schedules readily available;

timely dissemination of information pertinent to each integration event, such as test status, equipment availability, and results;

daily status meetings, with results immediately available.

Lesson 9

Prototyping a SOS can provide early insight into operational requirements and into the SOS systems architecture.

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