

NAVAL POSTGRADUATE SCHOOL

Monterey, California



CROSSBOW REPORT

CROSSBOW VOLUME I

by

The System Engineering & Integration Curriculum Students

December 2001

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MASTER OF SCIENCE IN
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EDITORIAL COMMENT

The students who prepared the work in this document graduated in December 2001. The NPS faculty accepted the responsibility for the final assembly and editing of this report. The extensive assistance of Professors “Chip” Franck, Patrick Parker, and Mike Sovereign is gratefully acknowledged. Ms. Rena Henderson contributed significant technical editorial assistance, and her contributions are also gratefully acknowledged. Editorial errors that remain are my responsibility. Credit and attendant responsibility for the content remain with the students (and their advisors).

An archive of all five volumes of the final CROSSBOW report is maintained at <http://www.nps.navy.mil/sea/crossbow/index.htm>.

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October 2002

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ABSTRACT

Distributing naval combat power into many small ships and unmanned air vehicles that capitalize on emerging technology offers a transformational way to think about naval combat in the littorals in the 2020 timeframe. Project CROSSBOW is an engineered system of systems that proposes to use such distributed forces to provide forward presence, to gain and maintain access, to provide sea control, and to project combat power in the littoral regions of the world.

Project CROSSBOW is the result of a yearlong, campus-wide, integrated research systems engineering effort involving 40 student researchers and 15 supervising faculty members.

This report (Volume I) summarizes the CROSSBOW project. It catalogs the major features of each of the components, and includes by reference a separate volume for each of the major systems (ships, aircraft, and logistics). It also presents the results of the mission and campaign analyses that informed the trade-offs between these components. It describes certain functions of CROSSBOW in detail through specialized supporting studies.

The student work presented here is technologically feasible, integrated, and imaginative.

This student project cannot by itself provide definitive designs or analyses covering such a broad topic. It does strongly suggest that the underlying concepts have merit and deserve further serious study by the Navy as it transforms itself.

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LIST OF ACRONYMS

ACN	Airborne Communication Node
AEW	Airborne early warning
AIT	Automatic identification technology
AMCM	Airborne mine counter-measures
AMRAAM	Advanced medium range, air-to-air missile
ARG	Amphibious ready group
ASROC	Anti-submarine rocket
ASCM	Anti-ship cruise missile
ASM	Anti-ship missile
ASW	Anti-submarine warfare
C4I	Command, control, communications, computers, and intelligence
CAIV	Cost as an independent variable
CBM	Condition based maintenance
CINC	Commander in Chief
CLF	Combat Logistics Force
COTS	Commercial off the shelf
CSAR	Combat search and rescue
CVBG	Carrier Battle group
EO/IR	Electro-optic/Infra-red
ESM	Electronic support measures
FAT	Fly away team
IOC	Initial Operating Capability
ISRT	Intelligence, Surveillance, Reconnaissance, and Targeting
JSF	Joint Strike Fighter
LT	Long Ton MCM Mine counter-measures
MIO	Maritime interdiction operations
MIW	Mine warfare
MNS	Mission Needs Statement
MOOTW	Military Operations Other Than War
MTI	Moving Target Indicator
MTTR	Mean time to repair
MTW	Major Theater War
NEO	Non-combatant evacuation operations
NPS	Naval Postgraduate School
NWC	Naval War College
OA	Operational Analysis
OL	Operational Logistics
ORD	Operational Requirements Documents
PGM	Precision Guided
PHMS	Prognostic Health Monitoring System
PLAN	People's Liberation Army Navy

PLANAF	People's Liberation Army Navy Air Force
PRC	People's Republic of China
RCS	Radar cross-section
RFI	Ready for installation
RFP	Request for Proposal
RHIB	Rigid hull inflatable boat
SAR	Synthetic Aperture Radar
SDE	Single definition engineering
SEAD	Suppression of Enemy Air Defenses
SEI	System Engineering and Integration
SL	SEA LANCE
SNT	Serial number tracking
SSC	Small Scale Conflict
SSS	Specialized supporting study
TAV	Total asset visibility
TOC	Total ownership cost
TSSE	Total Ship Systems
TW	Theater War
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Air Vehicle
UUV	Unmanned Underwater Vehicles
VADM	Vice Admiral
VOD	Vertical onboard delivery

I. CROSSBOW PROBLEM DEFINITION AND SCOPE

CROSSBOW: A high-speed, rapidly deployable, integrated and distributed naval force with a primary mission of forward presence, littoral sea control, forced access, and access maintenance, in low to moderate threat environments around the globe. CROSSBOW is capable of augmenting and enhancing carrier battle group operations in high threat environments.

The Naval Postgraduate School (NPS) CROSSBOW Report consists of five volumes, of which this is the first. Volume I is a product of the Systems Engineering and Integration (SEI) curriculum. It integrates and summarizes CROSSBOW's elements and missions and provides conclusions and recommendations. Volume II, a product of the Total Ship Systems Engineering (TSSE) capstone design course, provides a detailed report of the SEA ARCHER ship design. Volume III, a product of the Aeronautics and Astronautics Department's capstone design course, is a detailed report of the SEA ARROW aircraft design. Volume IV, a product of the NPS Graduate School of Business and Public Policy, provides a CROSSBOW logistics framework. Finally, Volume V is a repository for the SEI CROSSBOW Specialized Supporting Studies, as well as various background material and references.

A. BACKGROUND

1. CROSSBOW Project Inception

The CROSSBOW project took shape at the Naval Postgraduate School (NPS) in response to an enquiry by the President of the Naval War College (NWC) in October 2000. The central intent was to investigate the extent to which new technology and a changing world should cause the Navy to rethink the relative merits of dispersion versus concentration and the attendant economies of scale with regard to naval forces. Specifically, he proposed that NPS examine the feasibility of, and potential for, the "CORSAIR," a very small, high-speed aircraft carrier for distributed operations in littoral

waters.¹ The NWC had developed the notional concept, which featured high-speed aircraft carriers as a complement to large carriers, with an emphasis on obtaining access when opposed in littoral waters. Each CORSAIR would operate approximately seven Joint Strike Fighters (JSF) and two helicopters.

NPS students and faculty were given wide latitude in the conduct of the study. It is important to note that NWC provided no specific mission need. Rather, the students were tasked with taking a hard-nosed, skeptical look at the possible capabilities of CORSAIR. Briefing materials provided by the NWC and independent informal reviews of the NWC concept are presented in Volume V of this report.

2. Timing

An exploratory task of this magnitude required a level of interdisciplinary and interdepartmental collaboration not previously attempted at NPS. Although recent curriculum and organizational changes at NPS made it feasible, project planning for the yearlong study was constrained by existing academic program schedules (ship and aircraft capstone design classes), the part-time nature of the effort, and faculty availability. Therefore, some compromises and academic artificialities were unavoidable.

3. Project Organization

Figure 1 presents the NPS organizational elements contributing to the CROSSBOW project. The Systems Engineering and Integration (SEI) Curriculum requires that a significant project be undertaken by the student team in lieu of the usual Master's Thesis. The second group of students enrolled in the curriculum, SEI-2, was assigned CROSSBOW as its integration project.

¹ A 60-knot speed objective was imposed upon the team at the onset of the project. In the course of the study it became evident that the 60-knot objective had serious implications on ship design and cost, apparently without commensurate tactical benefit. Additional design iterations looking at a 40-50 knot range were not possible, given academic time constraints.

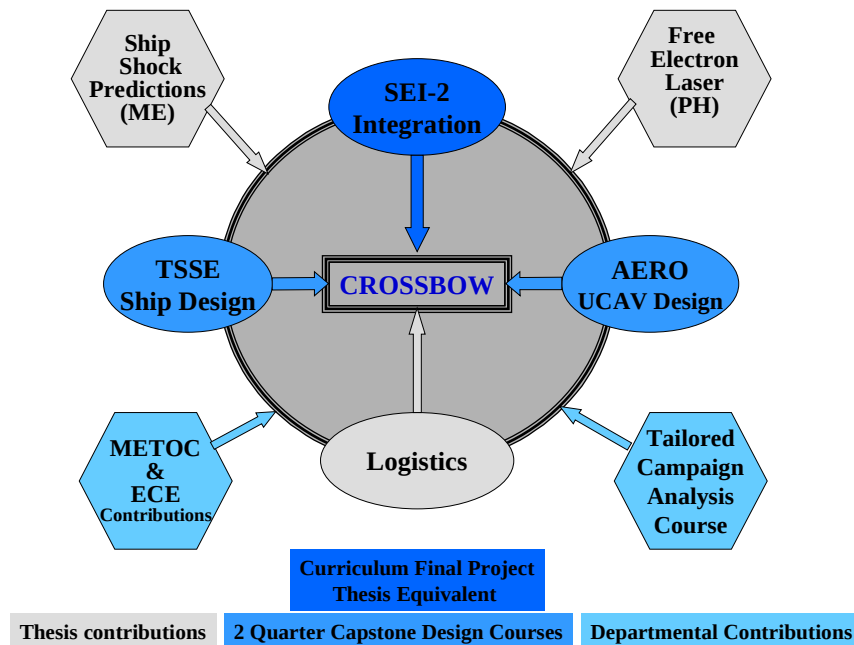


Figure 1. CROSSBOW Project Organization

The Total Ship Systems Engineering (TSSE) capstone ship design course, which draws from the Mechanical Engineering, Applied Physics, and Electrical Engineering Departments, provided the ship design team. The Aeronautics and Astronautics Department's capstone aircraft design course provided the aircraft design team. Four students from the Graduate School of Business and Public Policy produced a thesis on the requirements and cost of CROSSBOW logistics and maintenance. Two other supporting theses, one on a Free Electron Laser (FLE) as an "Electric Warship" weapon and the other on ship shock predictions for vulnerability and survivability, were contributed by the Physics and Mechanical Engineering Departments, respectively. The Operations Research (OR) Department made a significant contribution by tailoring an existing campaign analysis course for the express purpose of evaluating a notional CROSSBOW force in scenarios representing the full spectrum of conflict. Ten OR students were joined by the 15 SEI-2 and the four logistics students for this unique and productive course. In addition, the Electrical and Computer Engineering (ECE) Department contributed expertise and advice in the areas of radar cross-section, integrated antenna

design, avionics, electric drive, and electromagnetic interference. Finally, the Meteorology and Oceanography Department contributed expertise and advice on seasonal and geographic effects on ship, aircraft, and sensor performance.

Allied officer participation represented an important contribution to the CROSSBOW effort. More than 50 percent of the SEI-2 students were combat officers from the Singapore Armed Forces, and roughly 20 percent of the TSSE ship design class members were naval officers from Turkey. Valuable insight was gained from senior Naval leadership, Navy and government laboratories, and industry visitors who took time to participate in reviews and final briefings.

4. Constraints

Since NPS had been given no specific mission need for this effort, some students and several visitors believed that CROSSBOW was a solution looking for a problem. Instead, we considered it as a new operational concept for littoral warfare that required examination. In order to conduct an analysis, a preliminary notional force needed to be quickly specified by the student/faculty team. Due to academic schedules, much of the underlying operational analysis had to be done a full quarter after design efforts had commenced. As a result, our campaign analysis findings did not influence the aircraft design at all, but they did influence the ship-design effort.

Time constraints, coupled with faculty availability, led to the rapid development of several interim documents. Aircraft- and ship-design teams both needed a first look at requirements in order to start their design efforts; therefore, these documents were prepared on a tight schedule. These documents were not true Mission Need Statements (MNS), although they were labeled as such. Nor were they Operational Requirement Documents (ORD), though they had many elements normally found in an ORD. There was little formal analysis associated with the initial documents. They were circulated outside NPS for critical comment, which was useful, but, unfortunately, the documents seemed to have caused some confusion regarding the aim of the project. The intent of the project was not to generate a CROSSBOW MNS or ORD, but to examine the feasibility of, and potential for, a student-derived concept—CROSSBOW, loosely akin to NWC's

“Corsair.” We hope this report will be helpful to those who might develop an MNS or an ORD in line with these concepts.

B. FORCE LEVEL ASSUMPTIONS AND KEY CONSIDERATIONS

1. Introduction

This project was intended to assess a particular technological concept in a broad operational context. Assumptions and key considerations were either imposed upon the design team by higher leadership or developed to provide critical design factors. These directly impacted the CROSSBOW system. The key considerations represent a global view of the future and how certain technological trends will shape the Navy and the CROSSBOW system, in particular. This section gives a quick understanding of the rationale behind certain design decisions and the premises upon which the initial concepts were crafted. A more detailed discussion of key considerations may be found in Volume V.

2. Assumptions Made While Defining the CROSSBOW Force

a. Not a Carrier Battle Group (CVBG) replacement

CROSSBOW is not intended to and cannot replace the CVBG. Rather, it is a complementary force, which can relieve CVBG operational commitments in low- to moderate-threat littoral regions. CROSSBOW will have the capability to operate effectively as an independent force only in areas of low and moderate threat.

b. Composed of “combat-consumable” units, supported forward

As a group of many small combatants in a distributed environment, CROSSBOW is an asset readily deployable forward into littoral waters. It can be put in harm’s way to take hits as a “combat consumable”² in order to pave the way for other forces.

c. Capable of high-speed operations, up to 60kts

CROSSBOW is a high-speed, quick-response force. An operational speed of 60 knots was externally imposed as an operational attribute of the SEA ARCHER ship.

² A term introduced to us by VADM Cebrowski.

While the value of a 60-knot top speed (vice, say, 50) is probably not worth the cost, high speed is critical to the CROSSBOW concept.

d. A distributed force able to concentrate and disperse rapidly

A dominant feature of CROSSBOW is its ability to concentrate and disperse rapidly.

e. Threat projection is circa 2020

The enemy used in our analysis is a generic force with a military capability set at year 2020.

f. Key infrastructure is assumed in place

For CROSSBOW to operate as a distributed force, the key infrastructure for Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C⁴ISR) and logistics are assumed to be in place. This serves to facilitate the analysis of distributed systems. The unique requirements of CROSSBOW C4ISR and the logistics system will be addressed subsequently.

g. Technology freeze dates of 2012 and 2020

The technology freeze date for NPS Ship (SEA ARCHER), SEA LANCE II, and aircraft (SEA ARROW) design is set at 2012. The technology freeze date for all other less-integrated subsystems and weapons is set at 2020.

3. Key Considerations

a. Joint/Coalition Operations Constraints

Almost all modern operations are Joint Operations. CROSSBOW will have to be designed with Joint or coalition operations in mind. Examples include designing interfaces for communications with the Marines, Army, Air Force and other coalition multi-lateral forces.

b. Extensive use of Commercial Off-the-Shelf (COTS) Technology

Budgetary pressures and the acquisition climate will promote the use of COTS and joint cooperative development with industry.

c. Need For Automation

Since the 1980s, the U.S. Navy has experienced a downward trend in manning levels. However, the number of tasks required of the military has actually

increased. The use of automation to reduce manpower needs is an important CROSSBOW design consideration.

d. Environmental Constraints

Operations in the littorals are characterized by a high degree of clutter. The probability of an effective surprise attack is greatly increased in the littorals. Therefore, sensors onboard the CROSSBOW system must be able to detect these targets efficiently. A study of the regions of potential conflict shows that CROSSBOW must survive and operate in inclement weather. Increasing concerns for environmental safety impose efficiency requirements for the CROSSBOW system. Limited supplies of energy resources require that CROSSBOW be designed with fuel efficiency in mind. Alternative means of energy storage or power production should be investigated.

e. Nature of Future Warfare

As illustrated by the events of September 11, 2001, future warfare will be characterized by asymmetric threats. Similar asymmetric threats could be used against high-value naval assets. In addition to asymmetric threats, results from the campaign analysis indicate that saturation tactics can overwhelm CROSSBOW. The operational template for CROSSBOW must address both these issues in the context of future combat operations.

f. Logistical Issues

Due to reduction in U.S. overseas bases, CROSSBOW forces will have to rely on self-sustained logistics and/or Allies. Therefore, CROSSBOW must be compatible with the infrastructure, rules, and regulations of overseas ports and bases. Logistics support of CROSSBOW's surface combatants is a significant concern. CROSSBOW should include organic re-supply capabilities to reduce the burden on existing supply assets.

C. CROSSBOW MISSION AND CONCEPT OF OPERATIONS

1. Forward Presence

The changing political climate places increased international demands on the United States, and there has been a growing demand for naval involvement in Military Operations Other Than War (MOOTW) and Small-Scale Conflicts (SSC). This has

increased the Navy's operational tempo and placed great strain on naval forces. Commanders-in-Chiefs (CINCs) of the Unified Commands all desire a higher level of presence in their respective theaters than the Navy can provide.

CROSSBOW can be an effective independent and enabling force in *areas of low to moderate threat* where demands for firepower and operational coverage do not require the full-time presence of a carrier battle group (CVBG). CROSSBOW's distributed nature and speed can support some of the unfilled CINC operational commitments, while further expanding the Navy's area of influence to more regions of national interest.

2. The Littoral

Littoral operations constitute a fundamental tenet in the Navy's maritime strategy, as articulated in *Operational Maneuver From The Sea* and *Forward From The Sea*. The littoral is defined in the CROSSBOW context as a region extending from 100nm from shore to 100nm inland. This region is often cluttered with: coastal shipping and fishing, intense air traffic, oil rigs, small islands, shallow water influences, intense electronic radiation from land and sea (commercial and military), and a wide variety of threats from land, sea and air. All these can have adverse implications for naval operations. But demographic trends indicate that, by 2025, 90 percent of the world's population will be concentrated in littoral regions. Further, as numbers of U.S. overseas bases continue to decrease, the littorals must become the main access for the U.S. military into a crisis area.

3. Access and Escalation

The notion of littoral access can be viewed from different perspectives. The warrior's perspective is forcible access. This requires firepower and power projection superior to the opponent's denial capabilities. In contrast, the nearly continuous presence of a credible naval force in an area of national interest puts a nation in the more desirable position of access maintenance, thus reducing or negating the additional combat power needed to gain access. Access maintenance has the inherent advantage of deterrence. If necessary, however, it offers control of escalation when conflict becomes unavoidable.

It is rarely in the national interest to destroy completely a belligerent's defensive capability and communications infrastructure at the onset of conflict. If this can be

avoided by measured escalation, then, in the end, postwar rebuilding and stabilization tasks will be less expensive and faster. A small amount of combat power quickly applied can eliminate the need for larger forces that would arrive later.

Presence, deterrence and escalation control are missions that require a proactive deployment of forces. Forces performing these missions will find themselves in frequent small-scale exercises with allied nations or operating independently near-shore for days, weeks, or even months. Under low- to moderate-threat conditions, a naval force such as CROSSBOW is well suited for these tasks.

4. The CROSSBOW Advantage

The CVBG remains the force of choice to provide maritime dominance in the open oceans of the world and power projection ashore. It is also capable of effectively operating in the littorals, as are naval ARGs. But the number and complexity of low- to moderate-threat littoral regions of national interest, the increasing need to engage and exercise with less-capable navies, and the projected threat shape an operational niche for a naval force oriented specifically to littoral operations. The presence of this niche, combined with technological developments in unmanned vehicles and other forms of automation, led to the CROSSBOW concept. This specialized, low- to moderate-threat littoral force can potentially account for ten to 15 percent of the future naval force.³

The United States Navy has recently begun to explore seriously the concept of small, distributed littoral combatants, first referred to as Street Fighter and now known as SEA LANCE⁴. The concept currently lacks organic air cover and a viable scouting capability, both of which are critical for mission success⁵. CROSSBOW combines a SEA LANCE variant, SEA LANCE II, with SEA ARCHER, a small, high-speed UAV Tactical Support Ship (TSS) or “very small aircraft carrier,”⁶ and SEA QUIVER, a notional high-speed support ship. A significant synergistic effect is realized.

³ Comments by CAPT Wayne Hughes USN (Ret), 8 Nov 2001.

⁴ The NPS TSSE program designed SEA LANCE in AY 2000. The technical report is available at <http://web.nps.navy.mil/~me/tsse/files/2000.htm>

⁵ These issues were discovered during our campaign analyses, presented in Volume V.

⁶ “Small aircraft carrier” may not be an appropriate description for SEA ARCHER. Reasonable people might well prefer “UAV Tactical Support Ship”, which perhaps, better describes the platform. However, for the purposes of this report, “small aircraft carrier”, “small high-speed aircraft carrier”, and

Although designed to operate independently in low- to moderate-threat environments, CROSSBOW can also complement the CVBG during theater war. CROSSBOW will be expected to tackle many of the dull, dirty, and dangerous missions in order to help prepare the battle-space for following operations. It will be used to clear out and identify the coastal “clutter” and eliminate significant numbers of tactical targets in the littoral, freeing CVBG forces to focus on deep strike and more challenging targets. In short, CROSSBOW provides the “stunning” jab, while the CVBG delivers the “knockout” punch.

a. CROSSBOW Strategic Advantage: Forward Deployment Capability

The smaller ships of the CROSSBOW force can be forward deployed in packages sized for the region's threat and the level of national security interest. This capability is also important for effective engagement with nations having smaller navies.

CROSSBOW offers several tactical advantages.

b. Enhanced Survivability

CROSSBOW, as envisioned, has no “center of gravity” or single point of failure. This characteristic:⁷

- Denies the enemy the ability to defend with a single maneuver.
- Denies the enemy the opportunity to concentrate firepower and effort.
- Builds robustness—allows fleet to retain significant combat potential even after sustaining some losses.
- Allows more continuous operations.

c. Modularity and Flexibility

The flexibility and maneuverability resulting from the distributed nature of the CROSSBOW force, operating in small force units, allow it to respond simultaneously to multiple skirmishes within an assigned operating area.

d. Divided Assets, Integrated Firepower

“UAV Tactical Support Ship” are all synonymous descriptions of SEA ARCHER.

⁷ “An Analysis of Distributed Combat Systems,” Keith, Jude, Ho; CROSSBOW Specialized Supporting Study, December 2001.

CROSSBOW consists of 20 SEA LANCE II small combatants and the eight distributed SEA ARCHERs. CROSSBOW conducts coordinated and simultaneous air operations and can rapidly launch one large pulse of airborne combat assets on a wide range of missions (*128 unmanned vehicles; 16 MH-60s*), or many ‘small’ to ‘medium’ packages around the clock.

The force brings the following to the fight:

- 1020 x VLS Tubes (small 15-25nm Standard Missile variant)
- 80 x Ship Launched HARPOON Missiles
- 1024 x Small Smart Bombs (per day –all SEA ARROWS dedicated) ⁸
- 768 x Air-to Surface Missiles (per day –all SEA ARROWS dedicated)
- 512 x HARM circa 2020 (per day –all SEA ARROWS dedicated)
- 200 x ASROC (assumes 10 per SEA LANCE II)

This is a significant lethality, roughly comparable to a CVBG, but for only a single pulse.

e. Enemy Targeting Dilemma

CROSSBOW complicates the enemy’s information and target acquisition processes, through its numbers, size, and individual ship capabilities.

5. CROSSBOW Missions and Operational Concepts

CROSSBOW is designed to perform a myriad of missions and tasks in order to achieve its primary mission. A summary, organized by conflict type, is presented in Figure 1. Following are some CROSSBOW mission capabilities, also organized by conflict type. The final CROSSBOW force description is presented in Table 1.

⁸ SEA ARCHER magazine capacity not considered – these are maximum numbers by type. Trades will need to be studied to determine the best mixed weapon loads for a given scenario.

Force Components:

SEA ARCHER: Small High-speed UAV Carrier (45-60 knots ~600 ft / 14-15K LT)⁹

Terminal Defense:

Candidate Systems

- Rolling Airframe Missile (RAM)
- Electro-Magnetic Pulse (EMP) Weapons
- Free Electron Laser (FEL)
- Small-caliber stabilized gun
- Enhanced Ship Self Defense System (ESSDS)
- SRBOC decoy launching system
- Laser mine detection and avoidance system

SEA ARCHER Air Wing:

- 8 x SEA ARROW (6 operational / 2 spares)¹⁰
 - Designed for armed reconnaissance
 - 15,000 lbs each
 - Modular weapons payload¹¹
 1. 4 x 250lb small Smart Bombs
 2. 2 x AMRAAM AIM120 (350lbs ea.)
 3. 1 x Gun Pod – GPU-2A (M197) (600 lbs)
 4. 2 x HARM (Inboard ~1000lbs ea.)
 5. 3 x Jammer pods - new design (current ALQ-99 ~1000lbs ea.)
 6. 3 x Anti-Ship Missiles (ASM) current Air Launched Harpoon Inboard~1000lbs ea.
 7. Combinations of 3 variants of air -launched MCM ROVs
 - ~ 500lbs each
 - Hunter / Processor / Neutralizer
 - Helicopter or ship recovery
 8. Laser mine hunting module (<2500 lbs)
- 8 x Multi-mission support UAVs (~500 lb payload)
 - Med Altitude / Med Endurance (min - 8hrs on sta.)
 - Modular Payload
 1. Airborne Communications Node (ACN)
 2. Intelligence, Surveillance, Reconnaissance, & Targeting (ISR&T)
 3. Airborne Early Warning (AEW) (limited range capability)
 - Estimated max gross weight ~8000lbs
- 2 x MH-60 Multi-mission helicopters
 - Vertical Onboard Delivery (VOD)
 - Combat Search And Rescue (CSAR)
 - Anti-Submarine Warfare (ASW)
 - Airborne Mine Countermeasures (AMCM)
 - Anti-surface Warfare (ASUW)

SEA LANCE II: Small high-speed combatant (45-55 knots ~180 ft / 600-650 LT) – higher speed version of original SEA LANCE design without the tow – result of campaign analysis.

⁹ NPS Total Ship Systems Engineering (TSSE) designed ship

¹⁰ NPS Aeronautical Engineering Department designed UCAV

¹¹ At max fuel load (4300lbs) only 1500lbs of ordnance can be carried; however, at 50% fuel, range still exceeds 400nm and payload can be increased to 3550lbs. Only the 1st three payloads listed were investigated by the Aero design team, the remainder, are payloads Sea Arrow should be able to carry based on its basic performance characteristics.

○ ~48-60 hours endurance ○ SPY-3 Radar variant circa 2020 ○ 3 x Unmanned Underwater Vehicles (UUVs) ○ 1 for ASW ○ 2 for MCM ○ ~1000 lbs ea. ○ Armament: ○ 51 SM-X (SM-X = small, vertical launched, multi-purpose, 15 nm weapon) ○ Anti-Submarine Rocket System (ASROC) or circa 2020 equivalent ▪ May require trading SM-X missiles for space – depends on ship size ○ 4 x Harpoons ○ 2 x 30mm Gun Can refuel from SEA ARCHER or SEA QUIVER
<u>SEA QUIVER:</u> High-speed CROSSBOW support ship (35-40 knots ~700 ft / ~25K LT – Full load) ○ ½ AOE-6 baseline ○ ~10K tons fuel ○ Strictly a notional ship
<u>Force Composition by Scenario¹²:</u> By taking a notional force structure and conducting a series of campaign analysis mini-studies, the CROSSBOW force composition was tested. Sensitivity analysis resulted in the proposed force composition by scenario (Military Operations Other Than War (MOOTW); Small Scale Conflict (SSC); Major Theater War) below.

Table 1. CROSSBOW Force Composition

¹² Force composition is very scenario dependent. These results are only valid for the limited scenarios evaluated during student's Campaign Analysis class (see section II). Therefore, these numbers should be used with caution.

a. MOOTW: Humanitarian Missions and Crisis Response and Suppression

CROSSBOW could provide the following:

- Surveillance of littoral area of interest through use of UAV and ACN¹³ (Airborne Communications Node);
- Supplemental communications for local authorities where appropriate;
- Temporary emergency transportation where necessary;
- Physical protection where necessary through use of UCAV (Unmanned Combat Aerial Vehicle) and firepower where appropriate.
- Peacetime Search and Rescue Operations.

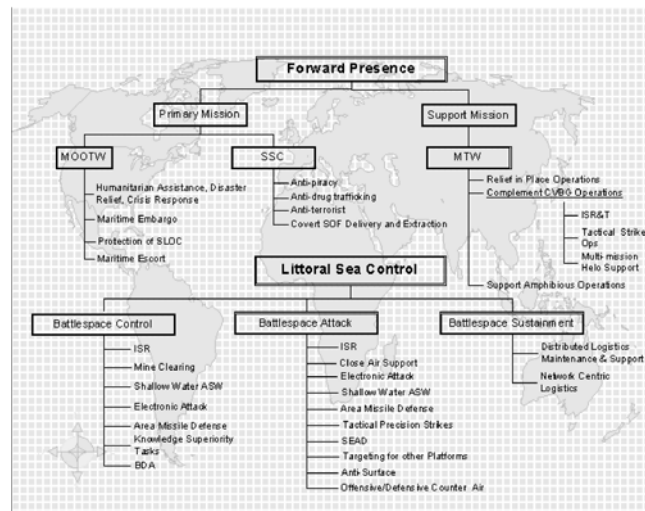


Figure 2. CROSSBOW Missions

b. Anti-Piracy and Drug Interdiction Operations¹⁴

CROSSBOW may be used to provide the following:

- Intelligence through use of surveillance assets;

¹³ Unmanned airborne communications modules acting as communications relay. Refer to Specialized Supporting Study by Foo Khee Loon in Volume V.

¹⁴ Depending on the threat involved, anti-piracy can be regarded as SSC or MOOTW

- Engagement and, if necessary, destruction of identified offenders through use of UCAVs or SEA LANCE II;
- UAV tracking of pirates and drug traffickers;
- Conduct of offensive operations against identified shore bases of offenders;
- Protection for potential victims of piracy through presence (deterrence) and swift response.

c. Smaller-Scale Contingencies (SSCs): b. Maritime Embargoes, Protection of SLOCS and Fast Maritime Escorts

CROSSBOW may be used in littoral operations to:

- Provide reconnaissance and constant surveillance through use of UAVs, UCAVs and SEA LANCE II;
- Support Coast Guard boarding and inspection teams;
- Engage forces that contravene agreements and treaties;
- Provide subsurface surveillance, localization, and prosecution through use of helicopters, SEA LANCE II and Unmanned Underwater Vehicles (UUVs);
- Protect and provide assistance to Allied commercial or military shipping.
- Accompany High Speed Vessels (HSVs) carrying Marine or Army forces to a scene of action and provide combat support in a SSC.

c. Anti-Terrorist Operations

CROSSBOW may be used in anti-terrorist operations to:

- Conduct Intelligence, Surveillance, Reconnaissance, and Targeting (ISR&T) operations in support of US Homeland Defense authorities;
- Use SEA LANCE II or UCAVs to provide physical security / screening against potential suicide boats or aircraft;
- When directed, use offensive firepower to engage and destroy identified terrorist assets at sea, on the land or in the air.

d. Special Operations

CROSSBOW would provide:

- ISR&T intelligence for planning;
- Special Operations team transportation via SEA ARCHER, SEA LANCE II, or combat support helicopters (MH-60);
- Special Operations team rescue capability;

- Firepower to engage and destroy enemy targets, where directed, in support of Special Operations;
- Airborne and sea borne logistics support.

e. Major Theater War (MTW) – Supplementing a CVBG

CROSSBOW could work with (supplement) and complement a conventional fleet in the following manner:

(1) Transition Phase. CROSSBOW can transit ahead of or in company with the CVBG using CROSSBOW assets to assist in:

- Airborne Early Warning;
- ISRT
- Offensive and Defensive Counter Air;
- Anti-Surface Warfare (ASUW);
- Vertical Onboard Delivery;
- ASW localization;
- Layered defense;
- Suppression of Enemy Air Defenses (SEAD);
- Destruction of Anti-Surface Missile (ASM) batteries.

(2) Pre-Ops Phase. This includes gathering of intelligence; use of UCAVs to provide armed coastal and littoral reconnaissance; use of SEA LANCE II to provide short range air defenses for the CVBG, if necessary; and clearing the cluttered surveillance picture created by small coastal traffic and fishing boats.

(3) Operations. The main aim of CROSSBOW when operating with a CVBG in MTW is to find and open a suitable stretch of the littorals for follow-on forces to conduct further operations.¹⁵ To accomplish this, CROSSBOW may be used in the following manner:

- Multiple probes along the littorals to locate suitable areas for follow-on operations;
- SEA ARROWs (UCAV) for SEAD to allow follow on air forces unrestricted passage into the area of operations;

¹⁵ Follow-on operations may include landing ground troops to execute operational maneuver from the sea, or for the CVBG to approach the land to provide deep strikes into enemy territory.

- Helicopters (MH-60) and other mine clearing assets (UUVs) to allow follow-on sea forces unrestricted passage into enemy littoral waters;
- UUVs and ASROC from SEA LANCE II for ASW;
- SEA ARROWs to engage enemy air assets;
- SEA LANCE II to provide an additional layer of air defense for the battle group;
- SEA ARROWs to engage enemy ships (ASUW);
- SEA ARROW to deliver of ordnance on tactical targets in the littorals to free CV assets for deep strike missions;
- SEA ARROW to provide additional armed reconnaissance capability to forces moving ashore.

D. MILITARY THREAT ASSESSMENT

1. Threat Overview

In 2020, military threats¹⁶ will generally feature upgraded and improved versions of existing weapon systems. However, weapon developers around the world will exploit commercial technology¹⁷ to achieve significant improvements in the following areas:

- Satellite-centered C4ISR;
- Missile defense;
- Reduced signatures (stealth);
- Information Warfare;
- Laser and Directed Energy Weapons;
- Anti ship cruise missiles;
- NBC (Nuclear, biological and chemical) weapons¹⁸.

¹⁶ This section focuses primarily on military threats from nation-states. Certainly non-state actors, such as terrorist organizations and drug cartels, can also pose national security threats. However, as military operations following September 11, 2001 illustrate, strength of the cooperating nation-states can be a major determinant of the capabilities of non-state threats. They have a great deal to do with resources available and security of organizational infrastructure.

¹⁷ A large body of literature identifies areas of commercial technology development with military potential. Most notably are Computers (including software and hardware research), Telecommunications Equipment, Biotechnology, Chemicals, Aviation, and Space.

¹⁸ Though outlawed by international agreements and treaties, the recent spate of anthrax attacks in the United States, and its apparent difficulty in coping with such an attack, will inevitably appeal to potential adversaries and encourage further research and developments into such technologies.

Also, advances in emerging technologies such as artificial intelligence, robotics, and superconductors can introduce the following capabilities:

- Long-range, precision-guided missiles and unmanned vehicles;
- Robots performing rudimentary tasks—e.g., clearing and laying of minefields;
- More effective use of the electromagnetic spectrum;
- Cheap Precision-Guided Munitions (PGMs);
- Very stealthy submarines with long-range (>500NM) torpedoes.

Given the rapid development and proliferation of technology, we can expect that future adversaries will be able to exploit these technologies and employ the following strategies, tactics and weapon systems in future military engagements:

- Saturation and exhaustion of defenses with missiles and other standoff weapons;
- Anti-Satellite Weapons;
- Small, fast, and expendable combatants;
- Sophisticated forms of mine warfare
- Violation of existing treaties and other international norms.

Results from our Campaign Analysis studies and discussions with senior officers and members of the Naval Postgraduate School faculty reaffirmed that the projected threats listed above are realistic.

A summary of key findings is listed below in the following subsections: (2) Current General Threat; (3) Potential Adversaries' Future Combat Potential; (4) Potential Adversaries' Capabilities Under Discontinuous Change; and (5) Considerations from Campaign Analysis.

2. Current General Threat

We expect that future engagements at sea, especially in the littorals, must contend with threats from Air, Land and Sea arms. However, naval threats will likely be the main concern for CROSSBOW. While, for a number of reasons, a comprehensive assessment of threats to CROSSBOW is beyond the scope of this study, we've used China as an

upper-bound proxy for naval threats to operations in littoral regions.¹⁹ As this section indicates, the current threat, though worrisome, is not a serious challenge to U.S. sea control, except in the littoral areas. However, there are serious efforts underway to (a) make that challenge in the littorals and (b) move it outward to the blue-water arena.

a. Blue Water and Power Projection Capabilities

China, a major weapon developer and supplier, is now replacing older, slower ships with newer destroyers and frigates²⁰. Most of the ships are Russian, or based on Russian designs, and capable of speeds of 30-35 knots. The latest acquisitions include units from the Russian *Soveremenny* class, which has three times the endurance of the *Luda* class and twice that of the *Luhu* class—with corresponding increases in blue-water and power projection capabilities. It is probable that the combat systems and technologies mentioned throughout this section will be made available to other nations, as well. In any case, CROSSBOW force will have to deal with such forces while deploying.

b. Sea Denial and Coastal Defense Capabilities

The most lethal anti-ship missile in the PLAN²¹ inventory is the supersonic *Moskit* SS-N-22. Besides anti-ship missiles, the *Sovremenny*, *Luhai* and *Luhu* classes of ship also carry torpedo tubes for anti-ship and anti-submarine purposes.

The submarine corps is one of the most significant PLAN combat arms. It is regarded as a highly cost-effective means for guarding Chinese maritime boundaries. The main anti-ship submarine in the littoral area is the *Kilo* class submarine. It has six 533 mm torpedo tubes, 18 53-system homing or wire-guided torpedoes, 24 AM-1 underwater mines or eight SA-N-5 "Arrow" standby anti-aircraft missiles.

PLAN mine stockpiles include vintage Russian moored-contact and bottom-influence mines, as well as an assortment of domestic types. China is believed to have acoustically activated remote control mine technology. This technology could allow

¹⁹ A more detailed analysis of threats in the year 2020 can be found in Volume V of this report.

²⁰ A number of these vessels are expect to be domestically produced.

²¹ People's Liberation Army Navy – The Naval Arm of the Chinese Military.

dormant mine fields to be laid in advance of hostilities and to be activated or deactivated as required.

The PLANAF²² has about 540 aircraft of different types. There are 11 air bases under the North Sea fleet, seven under the South Sea Fleet, and 13 within a 250-mile radius of Taiwan, with approximately 180 fighters. The PLA Air Force (PLAAF) and the PLA Naval Air Force (PLANAF) combined number over 400,000 personnel, 4,300 tactical fighters, 1,000 bombers and close air support aircraft, and 650 transport aircraft. However, the vast majority of the fighters are obsolete. The only fourth-generation aircraft currently in China's inventory is the Su-27 *FLANKER*. By 2005, PLA fourth-generation fighter aircraft are expected to number about 150 and constitute only about four percent of the fighter force.

The PLANAF currently has no confirmed Precision-Guided Munitions (PGMs) capability. Moreover, only its B-6D bombers and FB-7 fighter-bombers have a standoff strike capability. Finally, China's air defense forces will probably be limited to point defenses since there is no integrated national air defense network.

Coastal defense will also involve the PLAN Coast Guard, which is equipped with air defense, anti-ship missiles and gun batteries. It also has artillery units and 25 surface-to-surface missile regiments. The Coast Guard also operates the coastal surveillance system, which includes radars.

c. *Electronic and Information Warfare Capabilities*

The bulk of Chinese Electronic Warfare (EW) equipment embodies 1950s-1980s technologies, with only a few select military units receiving the most modern components. China's Information Operations (IO)/Information Warfare (IW) is in the early stages of research. It currently focuses on understanding IW as a military threat, developing effective countermeasures, and studying offensive employment of IW against foreign economic, logistics, and C⁴I systems.

²² People's Liberation Army Navy Air Force – The Naval Aviation Arm of the Chinese Military.

China has the capability to launch military photo-reconnaissance satellites. However, by Western standards, the technology is outdated. In particular, Beijing does not currently possess a real-time photoreconnaissance capability.

3. Nature of Future Threats

In general, future combat potential will combine current capabilities with new technology and combat equipment. It is likely that most military organizations will engage opposing naval forces first with low- to medium-performance systems, so as to exhaust the defenses, and then attack with a wave of high-performance systems.²³ Therefore, as technology advances, especially in guidance and range, the U.S. Navy is likely to face increasingly effective saturation attack threats.

The airborne threat to naval assets will likely comprise: (1) a few high-altitude aircraft attacking with precision guided bombs, missiles, and torpedoes; and (2) many low-altitude, mostly unmanned aircraft equipped with precision avionics and electronics to disrupt communications and/or targeting, as well as weapons to destroy critical C2 nodes.

Future submarines will be extremely quiet. By 2020, state-of-the-art submarines will become so quiet that detection can occur because of the *absence* of natural ocean sound. This will be overcome by ocean-masking technology that transmits the missing or blocked sounds at the proper amplitude.

We can expect great powers such as China, and smaller powers as well, to undertake energetic programs to exploit current and emerging technologies in modernizing their forces over the next quarter century.

a. *Less Conventional Threats*

In all likelihood, threats to deployed U.S. forces will not be limited to high technology. Many countries will lack the financial resources and foresight to develop, build and field weapons such as those listed above. This class of future rivals requires attention also.

²³ Volume 5 discusses in more detail additional capabilities that China will likely possess by 2020.

Chemical, Biological and other unconventional weapons can become weapons of choice for those states or organizations that prefer terrorist or rogue style attacks. In view of the events of September 11, 2001, it is clear that distributed threats are also dangerous and real. It is educational to view the attack from a military perspective. In this case, we can see the difficulties that any force would have dealing with a highly distributed, technologically sophisticated threat intent on attacking the center of gravity of any system it wishes to destroy.

4. Insights From Campaign Analyses

Campaign analysis provided a number of insights regarding both the probable threats and potential counters. The most important are listed here.

Submarines will continue to be a serious threat to any surface fleet even with an effective ASW capability. The submarine's first-launch capability makes ASW operations especially difficult to execute well.

Mine warfare is a very real threat. While it is difficult to simulate physical effects, the mere presence of mines delays attacking forces and requires the commitment of significant resources for clearing and avoiding the mines.

High degree of reliance on satellites for command and control operations is a "center of gravity," which, upon destruction, would significantly reduce the capability and staying power of U.S. naval forces.

Saturation is one of the key methods of countering a technically superior enemy. In our analysis, numerous small combatants attacking simultaneously could damage or destroy a significant portion of the CROSSBOW battle group. "Quantity has a quality all of its own."²⁴

Aircraft can inflict a great deal of damage on a surface fleet. Hence, one of the more important lessons or challenges is to ensure that the CROSSBOW UCAV will have air-to-air as well as anti-ship capabilities.

A single Free Electron Laser on each CROSSBOW ship would handle a close-in threat much better than current defensive systems would. Likewise, it is reasonable to

²⁴ Comment attributed to Josef Stalin.

expect that, should a competitor successfully field such a system, CROSSBOW offensive capability would be significantly reduced.

5. Bottom-Line Assessment

Taking China as a proxy for potential threats, we've found only limited capacity to contest sea control beyond the littoral region bordering that country. However, we can expect PLAN combat capabilities to improve greatly between now and 2020, especially in its ability to engage in power-projection missions. It will very likely have steadily increasing capabilities to contest U.S. sea control in both littoral and blue-water arenas. Furthermore, we can expect other powers to behave in a similar manner. Although not all nations have China's economic potential, they will have access to the same technology and will likely have access to equipment made in China.

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II. CROSSBOW CAMPAIGN ANALYSIS

This section provides an overview of CROSSBOW Campaign Analysis and the results that affect the CROSSBOW force structure, missions, and capability requirements. Student briefs on each scenario, along with detailed explanatory notes, are presented in Volume V.

A. THE JOINT CAMPAIGN ANALYSIS COURSE

The NPS Operations Research (OR) Department offers the Joint Campaign Analysis course, primarily to Operations Analysis (OA) and Operations Logistics (OL) students. The course objective is to study:

the development, use and state-of-the-art of campaign analysis in actual procurement and operations planning. The emphasis is on formulating the problem, choosing assumptions, structuring the analysis, and measuring effectiveness.²⁵

During the summer quarter 2001, this course was tailored expressly to evaluate a notional CROSSBOW force in scenarios representing the full spectrum of conflict. Ten OA students joined 15 SEI-2 and four logistics students for this unique and productive course.

1. What is Campaign Analysis?

Campaign Analysis is the study of the first-order effects generated by a conflict between heterogeneous forces in a series of encounters conducted over time and covering a wide geographic area.²⁶

It presents its users with a variety of tools, techniques and procedures to assist in military planning. It finds most applicability in a world where the threat is uncertain and the situation fluid. In its purest form, Campaign Analysis makes use of simple mathematical or logical relationships to model battle encounters. This is the academic analog of a commander on the field trying to calculate how much, and what forces he needs to commit in order to win a battle.²⁷

²⁵ Naval Postgraduate School 2001 General Catalog

²⁶ Joint Campaign Analysis, Book I – Student Text, Naval Postgraduate School, OR Department, 6 Dec 99.

²⁷ “...of Bishops, Knights, and Pawns...”, Keith Jude Ho, Naval Postgraduate School, Oct 2001.

2. Naval Salvo Model²⁸

Several of the CROSSBOW scenarios involved combat encounters with emphasis on surface search and strike. The Naval Salvo Model was the primary tool used by the student teams to analyze CROSSBOW forces. It presents a naval engagement as an exchange of missiles, accounting for both fleets' total offensive capability, defensive capability, and staying power.

3. Limitations of Campaign Analysis

Campaign analysis is a decision support tool, where results, granularity, specific inputs and accurate assumptions are required. Scenarios and model inputs must be rigorously understood because they affect the analytical results. Results are highly scenario-dependent, and the more detail one wishes to obtain, the greater the dependence on scenario-specific inputs. The old "Garbage-in = Garbage-out" analogy works as well for Campaign Analysis as it does elsewhere. Hence, numerical results from Campaign Analysis must be used with caution. No attempt to treat numbers and figures with "biblical" rigidity was intended. Rather, significant trends and concept validation are the useful products drawn from the numerical results.

4. Student Mini-Studies

At the conclusion of the Joint Campaign Analysis course, faculty put students to the test with small-team mini-studies. These studies force the students to apply the tools and methods learned. In the case of CROSSBOW, a small student-faculty team developed five relevant scenarios. Those scenarios were examined by seven student teams (two scenarios received double attention). Each student team consisted of two SEI-2 students, at least one OA student, and in four cases, a logistics student.

B. CROSSBOW MINI-STUDIES

1. Mini-Studies Objectives

²⁸ Developed by Capt Wayne Hughes of the Naval Postgraduate School. More commonly known as the HUGHES SALVO EQUATIONS.

The objective of the assigned set of mini-studies was to derive collective insights as to the feasibility and suitability of a very small aircraft carrier as a complement to the main U.S. Navy carriers and missile striking forces regarding:

- Missions and tasks of the aircraft ("SEA ARROW") flying from the carrier ("SEA ARCHER") and accompanied by a logistics capability ("SEA QUIVER") in cooperation with an inshore combatant capability ("SEA LANCE"), which together are known as "CROSSBOW."
- Attractive combinations of each force element, some viable tactics for the combinations, and the Intelligence, Surveillance Reconnaissance (ISR) and Command and Control (C²) networks implied by the force configurations.

By design, the mini-studies did not analyze cost effectiveness, nor did they include any trade analyses between CROSSBOW and other elements of the Navy.

All scenarios took place in the year 2020. This is far enough in the future to design a CROSSBOW force for littoral warfare with an initial operating capability (IOC) of 2012 and to construct the forces in sufficient numbers to play in the scenarios. Table 3 presents the notional CROSSBOW force structure used for the scenarios. Student teams were given the latitude to make their own assumptions where additional detail was necessary for a specific analysis. Additionally, teams altered configurations, payloads, and numbers, once a baseline analysis was complete, in order to identify sensitivities.

• 8 x SEA ARCHERs - Small High-speed (60 knots) UAV Carrier
• SEA ARCHER Air Wing: ○ 8 x SEA ARROW (UCAVs) ▪ 4 configured for strike ▪ 2 configured for SEAD ▪ 2 configured for Intelligence Surveillance Reconnaissance & Targeting (ISR&T) ○ 8x UAVs for surveillance and C3 ○ 2 x MH-60 Multi-mission Helicopters OR 2 AH-1Z Attack Helicopters
• 20 x SEA LANCE ○ 51 SM-x Dual Purpose Missiles (surface-to-surface & surface-to-air) ○ 4 Harpoon Missiles ○ 30 mm Gun Note: SEA LANCE (SL) was designed by NPS in 2000 and it included a tow that contained the Expeditionary Warfare Grid, however the tow portion of SL was not employed for the purposes of the CA class.
SEA QUIVERs – numbers driven by analysis results - Same capacity as ½ an AOE-6

Table 2. Notional Crossbow Force Composition

2. Mini-study Scenarios of Military Operations Other than War (MOOTW) and Small Scale Conflict (SSC)

a. *Maritime Support of Allies: Convoy Operations in the Mediterranean*

In this scenario, Israel is attacked by a coalition of Arab states, and Turkey comes to Israel's aid. The U.S. is asked to keep the air- and sea-lanes open for vital cargoes throughout the length of the Mediterranean. There is no CVBG available nearer than Norfolk, and the European Union stays neutral. U.S. forces consist of four Aegis ships, four SSNs, a Marine Expeditionary Unit (Special Operations Capable), CLF ships, and CROSSBOW.

b. *Anti-Piracy Operations in the Malacca Straits*

A CROSSBOW force, using Singapore as a base of operations, conducts operations to suppress piracy in the Straits of Malacca. In one variation, Indonesia permits SOF raids on pirate strongholds in Sumatra that have been identified by air and sea surveillance.

c. *Response to Multiple Insurrections in Indonesia*

Instability in Indonesia leads to an outbreak of several insurrections on various islands. CROSSBOW forces are dispatched in reaction.

3. Mini-study scenarios of Theater War (TW) and Major Theater War (MTW)

a. *Maritime Conflict in the Mediterranean*

Two U.S. Allies in the Mediterranean are poised for a major showdown over islands in the Aegean Sea. The U.S. is committed to deterring conflict by providing a naval presence in the region. Should deterrence fail, the U.S. is poised to strike against the aggressor nation. U.S. Forces include CROSSBOW, AEGIS ships, and a Carrier Battle Group. The operation is conducted in the littorals with U.S. Forces prepared to combat the aggressor along her own coast. Aggressor assets are mainly land-based attack aircraft, destroyers with missiles, missile ships, patrol craft and submarines.

b. *Peer Competitor (Independent Maritime/Forestalling Operations)*

The Peoples Republic of China (PRC) is a dominant force in East Asia. As of 2015, Taiwan has reunified with the PRC. The PRC has acquired a formidable sea denial capability, and due to trade and dependency on oil imports it is in the process of building a sea control capability in East Asia and the South China Sea. Their aim is to envelop Malaysia and Singapore by first seizing the Spratleys. As the scenario unfolds, they have positioned a company of infantry, a battery of 16 Anti-Ship Cruise Missiles (ASCMs), and two squadrons of fighter/attack aircraft on the Spratleys, with further buildup imminent. A substantial part of the 2020 PRC Navy, consisting mainly of coastal craft, destroyers, frigates, and diesel submarines, defends the approaches and sea lanes to transform the Spratleys into a bastion and subsequent use as a springboard into Malaysia.

The U.S. has decided to employ CROSSBOW forces, two CG-47s, and two SSNs based in Singapore to disrupt and forestall the impending buildup. U.S. surveillance provides strategic and operational intelligence, but not tactical (targeting) information. The nearest CVBG is a seven-day transit away. Singapore has committed to support the U.S. Navy militarily and logistically. Major U. S. forces will be dispatched immediately, the nearest of which are U.S. Air Force long-range bombers in Guam and other forces in Japan, Okinawa and Hawaii. There are no U.S. forces in a reunified Korea.

c. Peer Competitor (CROSSBOW as a Complement to the CVBG)

This scenario is the same as (b) above, with the exception that there are two carrier battle groups in the area and the CROSSBOW force joins with the CVBGs. However, the PRC ground and air presence in the Spratleys is now increased to a brigade, 50 ASCMs, plus six squadrons of fighter/attack aircraft, all in well-protected and hardened sites. Additionally, one-half of the presumptive 2020 PRC naval forces are committed.

C. FINDINGS AND RECOMMENDATIONS

1. Universal Findings²⁹

a. Numbers Can Buy Staying Power³⁰

An analysis of staying power showed that in most cases adding one ship to the distributed force was equivalent to increasing the forces' per-unit average staying power by about 12 percent (this, of course, varies by scenario).

b. Littoral Warfare

In littoral warfare, where the enemy can be expected to have large numbers of missile boats, a distributed task force will outperform a task force that has

²⁹ Universal findings, as presented here, are an edited version of those presented in "An Analysis of Distributed Combat Systems", a CROSSBOW Supporting Study by Keith Jude Ho, which can be found in Volume V of this report.

³⁰ Staying power is defined as the number of missile hits (or weight of ordnance) needed to put a ship out of action.

most of its assets concentrated in a few platforms. The Measure of Performance used in this case was the fraction of forces surviving after missile exchanges.

c. *A Complementary Strategy*

When distributed forces were used as a complement to the “un-balanced” or concentrated fleet, the overall survival fraction significantly improved. This was shown mathematically with the Salvo Equations and the other models used. The reason this occurs is that when both forces are used together, the distributed task force “dilutes” the enemy’s fire and draws away some missiles, which would otherwise have been targeted only at the high-value targets.

d. *Area of Coverage and Response Time*

In operations that cover a large area, a distributed force is preferable. This finds particular relevance in anti-piracy operations and similar missions. It is important to note that for a distributed force to be effective, not only must it be able to disperse, but it also must be able to concentrate on demand. Therefore, we conclude that an effective distributed force is one that is able both to disperse and concentrate on demand. The rate with which dispersion and concentration must occur was not clear from the mini-study.

e. *Logistical Limitations*

A ship constructed for use in a distributed fleet must be small, which limits endurance, range and payload. Therefore, a distributed force must be complemented by an appropriate logistics concept in order for it to be effective.

2. Specific Findings

a. *SEA ARCHER*

- Terminal Defense: Results indicate that even with SEA LANCE escorts and airborne coverage from SEA ARROWS, the SEA ARCHER should have a terminal defense capability (soft kill and point defenses) in order to improve survivability, even in moderate threat environments.
- Fueling: In order to maintain the level of flexibility and endurance desirable in the CROSSBOW force, the SEA ARCHER must be capable of refueling the SEA LANCE.

- Mine Warfare: An organic mine detection and avoidance system would facilitate quicker responses when operating in mine-danger areas.
- Speed: The payoff associated with a 60-knot operational speed was not evident. However, one analysis did indicate a reduction in the probability of a successful submarine engagement as speed increased. Ship design trade studies should examine speed and the associated benefits as a function of cost over the range of 45 to 60 knots.

b. The SEA ARCHER Air Wing

- ISR&T: Superior scouting was so crucial to success that the mini-study teams recommended that a medium-endurance UAV, dedicated to Intelligence, Surveillance, Reconnaissance, and Targeting, be included in the air wing.
- Air Wing Command and Control: Command and control of large UCAV/UAV strike and surveillance packages are recognized as significant issues. Further research by the CROSSBOW team is recommended.
- SEA ARROWs and Anti-Ship Missiles (ASMs): There was a substantial synergistic effect achieved when SEA ARROWs, carrying two or more ASMs, and SEA LANCES were teamed against small surface combatants. The SEA ARROW should be designed to carrying at least two ASMs as a payload option.
- SEA ARROW in the Counter Air Role: When configured solely for the counter air mission, SEA ARROW should be designed to carry three or more air-to-air missiles (AMRAAM or equivalent).
- SEA ARROW in the Air-to-Ground Role: The strike configuration of 4 x 250 lbs Small Smart Munitions was deemed a minimum. The Suppression of Enemy Air Defense (SEAD) mission was not directly assessed, but was recognized as critical for any independent operation requiring forced access.
- Number of SEA ARROWs: In two independent cases, sensitivity analysis indicated that six SEA ARROWs per SEA ARCHER Air Wing was optimal. However, since very little is known regarding SEA ARROW reliability and maintainability, we recommended that the Air Wing have minimum of six operational SEA ARROWs, with two spares on board.

- Helicopters: Helicopters were only directly evaluated in one scenario (anti-piracy), in which they played a key role. However, their value was not overlooked, as they were key contributors in CROSSBOW ASW and Mine Warfare (MIW) capability estimates. Also, helicopter contributions to logistics efforts were critical. Additional analysis is required to determine if a dedicated attack helicopter is necessary and worth the additional cost, logistic burden, and operational complexity.

c. SEA LANCE

- Speed: The SEA LANCE must be capable of operating at speeds compatible with SEA ARCHER.
- Endurance: The 24-hour SEA LANCE combat endurance limit created a logistics and operational burden during combat engagements. Therefore, it is recommended that the SEA LANCE combat endurance be increased to 48-60 hours at moderate to high transit speeds.
- Fueling: In order to maintain the level of flexibility and endurance desirable in the CROSSBOW force, the SEA LANCE must be capable of refueling from the SEA ARCHER. Therefore, SEA LANCE and SEA ARCHER should burn the same type of fuel.
- Mine Warfare: Addition of an organic mine detection and avoidance system would provide greater operational flexibility in mine-danger areas.
- ASW Weapons: One team recommended that some of the 51 small dual-purpose missiles be traded for up to ten ASROC launchers. Additional analysis is recommended prior to making such a change.
- SEA LANCE II: *SEA LANCE requirements, proposed by the CROSSBOW team, cannot be accommodated by the existing SEA LANCE I design developed last year by the TSSE curriculum.³¹ Therefore, for the purposes of the CROSSBOW project, a notional SEA LANCE II design of about 600 tons is favored.*

d. SEA QUIVER

³¹ See <http://web.nps.navy.mil/~me/tsse/files/2000.htm> for a complete report.

- Number of SEA QUIVERs: As expected, the number of SEA QUIVERs required varied by scenario, from one to four.
- Size: From the vulnerability perspective, the SEA QUIVER logistical support vessel should resemble the SEA ARCHER in size and speed. Unfortunately, high-speed hull designs tend to be weight-limited rather than volume-limited. We found it impossible to design a bulk carrier that could achieve a sustained 60 knot speed. Therefore, we cannot analytically support the assumption of an operationally compatible SEA QUIVER. This conclusion, coupled with project time constraints, led the team to conclude that the SEA QUIVER design should be left to future efforts. For the purposes of the CROSSBOW project, we assumed SEA QUIVER to be equivalent in capacity to 50 percent of an AOE-6 class supply ship (26,000 tons) with a speed of 35-40 knots.
- Alternatives: Any SEA QUIVER alternative must consider the nature of distributed systems. The alternative of distributing the SEA LANCE II fueling task amongst the eight SEA ARCHERs certainly lessens the challenge of keeping the force fueled, but it does not solve the larger logistics problem. Unfortunately, further investigation is beyond the scope of the CROSSBOW project.

III. FINAL CROSSBOW CONFIGURATION & CAPABILITIES

A. SUMMARY OF SEA ARCHER CAPABILITIES & CHARACTERISTICS³²

SEA ARCHER, the ship design component of the CROSSBOW project, was designed and developed by students in the Total Ship Systems Engineering (TSSE) curriculum.³³ This, their 2001 capstone design project, was the tenth since the program's inception and the first to be developed in a broader, campus-wide collaborative environment.³⁴ The project grew out of a Naval War College initiative to explore a concept called CORSAIR, a small aviation-capable ship carrying Short-Take-Off and Landing (STOL) Joint Strike Fighters (JSFs) for littoral operations. CORSAIR was envisioned as contributing to the Navy's capability to defeat an adversary's access-denial strategy by providing air cover for small littoral combatants, such as the SEA LANCE.³⁵

Emergence of Unmanned Air Vehicles (UAVs) and Unmanned Combat Air Vehicles (UCAVs), continued U.S. Navy focus on the littorals, desirability of force distribution, need for operational cost reduction, and the advent of Network Centric Warfare (NCW) all point toward re-evaluation of the conduct of future littoral aviation operations. These considerations also highlight the advantages of distributed air operations conducted from smaller ships; however, there are currently no systems in the U.S. Navy that can provide this capability. Given this background, our bottom-up design

³² A complete report on the SEA ARCHER design can be found in Volume II.

³³ The program includes students enrolled in three NPS curricula: Mechanical Engineering, Electrical and Computer Engineering, and Combat Systems. The faculty ensure that all design projects provide an opportunity for students from each of these curricula to apply what they have learned in their individual domains while participating in a wider-scope team design.

³⁴ A major purpose of the TSSE capstone design project is to give experience in the design process as applied to a large, complex-system Navy ship as the focus. An additional major goal is for the students to develop and exercise the leadership and cooperative skills needed to perform a complex design as a team. The design produced should be interesting and innovative, and it should spur discussion and thought in both Navy and industry circles.

³⁵ SEA LANCE was the subject of the 2000 TSSE capstone project, and was done in response to a Naval Warfare Development Command (NWDC) initiative, "STREETFIGHTER."

of SEA ARCHER supporting a primarily UAV/UCAV air wing in a moderate threat environment is a first attempt to address these needs.

SEA ARCHER also can work effectively with (or within) CVBGs. Saturation attacks have long been recognized as one of the most serious emerging threats to naval battle groups. The worldwide inventory of anti-ship missiles is expected to grow in both number and sophistication in the coming years as costs go down and technology proliferates. These missiles can be launched from ships, aircraft, and land (from fixed sites or mobile platforms). By proceeding into the littoral waters ahead of the CVBGs, SEA ARCHER can provide formidable defense suppression. Moreover, equipped with suitable electronic devices, the CROSSBOW force can greatly increase the enemy's targeting problem by proliferating both real and false targets, thereby drawing down the number of enemy anti-ship missiles in the early stages of the conflict. Thus, initially the CVBG can stand off, taking full advantage of its range and firepower, as well as benefiting from the increased defensive battle-space.

The operational requirements for the SEA ARCHER design included an air wing (eight UCAVs, eight UAVs and two helicopters), a deployment range of 4000 nm at 50 knots, and a maximum speed of 60 knots. We also set a manning level of not more than 150 personnel.

The air cushion design selected to meet these requirements displaces 13,500 measurement tons with a length of 181 meters and beam of 59 meters. Installed horsepower of the gas turbines is 327,000, more than a nuclear aircraft carrier. SEA ARCHER meets the demanding speed requirements of the Operational Requirements Document (ORD) by merging a catamaran hull with a surface effect ship's air cavities.

When filled with air by high-volume compressors, the cavities in each hull support up to 85 percent of the ship's weight, cutting the ship's draft in half and greatly reducing underwater resistance. The ship is propelled by a combination of six gas turbine engines driving six hydro-air drive propulsors. These vectored-thrust propulsors give the ship the ability to get underway without tugboats. The propulsion plant can be operated in various lineups to achieve a top speed of over 60 knots without sacrificing fuel efficiency at lower speeds.

Significant manning reductions were achieved with an unmanned flight deck and a computer-controlled, automated hangar deck. The fully enclosed hangar bay provides storage for all aircraft, maintenance areas, and a pit stop system where refueling, rearming, and reconfiguring functions occur. Other automated functions include the use of robotic “trackbots” and “towbots” for aircraft movement, as well as automated weapons handling and loading. Aircraft are launched with an Electromagnetic Aircraft Launching System (EMALS) catapult or can be launched without catapult assistance when SEA ARCHER’s speed is used to create a wind over deck greater than 40 knots. Fully enclosed elevators allow for corrosion-control water wash and CBR decontamination of aircraft in the elevator.

Reductions in manning were also achieved through a high degree of automation in other functions, including damage control. Also, a significant portion of SEA ARCHER maintenance is designed to be performed by outside activities. We estimate total manning of the SEA ARCHER to 128 officers and sailors.

SEA ARCHER has an inner-layer defense provided by a free-electron laser (primary air defense) and stabilized small-caliber gun system (primary surface role) with enclosed decoy launchers. Medium-layer defense employs air/surface capable missiles. This is supported by a new, small, unmanned surface craft capable of air and surface engagement as well as forward mine detection. SEA ARROW, helicopters, and SEA LANCE provide outer-layer defenses. Sensor suites include 3D volume-search radar, multi-function radar, Infra-Red Search & Track, and electro-optical systems. Command and control is supported by an enhanced Cooperative Engagement Capability (CEC) integrated with a ship self-defense system for air, surface and subsurface warfare.

It was clear from the beginning that the 60kt maximum speed capability for SEA ARCHER would be a major design driver. Further, it quickly became evident that 60 knots could not be sustained for extended periods due to fuel consumption. However, the advantage in maneuver warfare provided by a limited-duration sprint capability was deemed important enough to keep 60 knots as the top speed requirement. This led to the choice of the HARLEY SES hull form over the other alternatives seriously considered (high-speed catamaran and pentamaran). The results of the design process also

highlighted the significant penalty that must be paid for such speed. The propulsion system required to propel the nominal 15,000 LT SEA ARCHER at 60 knots is larger than the propulsion system required to propel a nominal 100,000 LT aircraft carrier at 35 knots, with a corresponding need for fuel tanks disproportionate to the size of a 15,000 LT conventional ship. Therefore, the 60-kt capability does not, in retrospect, seem worth the design trades it necessitated. That design specification is, at minimum, a question for further analysis.

Because the SEA ARROW UCAV had the ability to take off (with a 40-kt wind over deck) in 400 ft, we provided that takeoff length on the flight deck so that UCAV operation would not be dependent on launcher availability. Also, the only resistance and powering data available to the team for this hull type was based on specific combinations of naval architectural characteristics, such as length-to-beam ratio. In order to enhance the validity of the major “scaling up” required for the hull, the same ship geometry was maintained, and this, coupled with the 400-ft takeoff length, resulted in a ship that has excess volume for its payload.³⁶

While payload weight was not a major factor in the design, the fuel load required to meet the deployment profile (to include refueling escorts) was a major weight challenge. Because of this, the ship is weight- (not volume-) limited, and further design integration can be expected to reduce the excess volume in the ship.

SEA ARCHER, as designed, would be part of a layered engagement concept for both strike and defense. That layered concept would utilize technology currently being developed for the Navy. However, some systems specific to SEA ARCHER’s ORDs are also proposed.³⁷

From the tables below, it is evident that SEA ARCHER would be heavily dependent on defense systems aboard SEA LANCE II since SEA ARCHER’s combat systems would provide self-protection only to 30km.³⁸ This concept is workable only if

³⁶ The payload associated with eight UCAVs, ten notional UAVs and two helicopters is relatively small.

³⁷ See Appendix H and Volume V for details.

³⁸ This notional ship design is different from the original SEA LANCE in that it would match the speed and endurance of SEA ARCHER. It would also have a larger complement of missiles to provide a

SEA ARCHER units can take full advantage of distributed operations while having the ability to share information seamlessly. That would increase the coverage of the taskforce (operating as a fully cooperative whole), enhancing combat effectiveness and increasing survivability.

	<i>Range</i>	<i>SEA LANCE II</i>	<i>SEA ARCHER</i>
Outer Layer	200 km		SEA ARROW
Middle-Layer	50 km		SEA ARROW
Inner-Layer	30km	Super SEA Sparrow Missile, Harpoon	Super SEA Sparrow Missile / USC Missiles
Close-In	5 km	RAM	RAM now FEL later

Table 3. Layered Strike and Air Defense Concept for CROSSBOW Taskforce

	<i>Range</i>	<i>SEA LANCE II</i>	<i>SEA ARCHER</i>
Outer Layer	>200 km		SEA ARROW
Middle-Layer	>50 km	Harpoon / Medium Range Missile	
Inner-Layer	30km	Super SEA Sparrow Missile	Super SEA Sparrow Missile / SEA ARCHER's Unmanned Surface Craft Missiles / Helo Missiles
Close-In	5 km	Small Caliber Gun System	Free Electron Laser / Small Caliber Gun System

Table 4. Layered Surface Engagement Concept for CROSSBOW Taskforce

higher capability in both self and task force protection, coupled with sensor suites to match the missile and threat environment. As a result, it would have about 50 percent more displacement (approximately 700 tons) and would not include the expeditionary warfare grid.

	<i>Range</i>	<i>SEA LANCE II</i>	<i>SEA ARCHER</i>
Middle-Layer Defense	>50 km		Helicopters
Inner-Layer Defense	15km	Torpedoes, ASROC	

Table 5. Layered Sub-Surface Defense for CROSSBOW Taskforce

B. CROSSBOW AIR WING CAPABILITIES & CHARACTERISTICS

1. Background

The CROSSBOW air wing, embarked on 8 SEA ARCHER UAV Tactical Support Ships, is comprised of 8 multi-mission SEA ARROW, Unmanned Combat Air Vehicles (UCAVs), 8 multi-mission support UAVs, and 2 MH-60 multi-mission helicopters for each SEA ARCHER. CROSSBOW mission analysis, campaign analysis, distributed force C⁴I requirements, operating envelope and environment, and vehicle parametric constraints contributed to platform selection. Figure 3 shows the aircraft that comprise the SEA ARCHER air wing.



Figure 3. SEA ARCHER Air Wing Aircraft

2. SEA ARROW³⁹

SEA ARROW Unmanned Combat Air Vehicle (UCAV), a product of the NPS Aeronautics and Astronautics Department's Capstone Aircraft Design course, is a highly maneuverable aircraft designed for Armed Reconnaissance and Battlefield Interdiction. Figure 4 presents four views of the SEA ARROW.

³⁹ All specifics on the SEA ARROW design are products of the NPS Aeronautics and Astronautics Department's design team. Detailed design information can be found in Volume III.

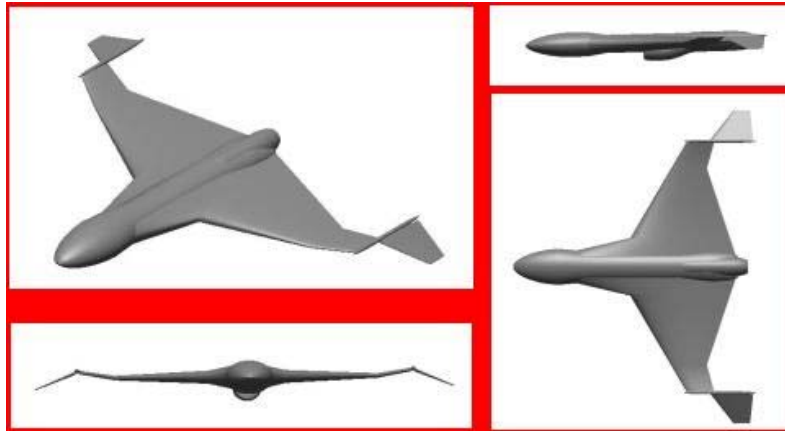


Figure 4. Four Views of the SEA ARROW

A detailed analysis using Quality Functional Deployment was used to determine the critical design parameters. Based on the design requirements, the most critical factors were found to be takeoff distance, endurance, payload weight, and size. To this effect, the use of composites, Life Cycle Costs (LCC), Mean Time Between Failure (MTBF), and Mean Time to Repair (MTTR) all played crucial roles finding a design that was relatively low-cost, easy to maintain, and, for the most part, expendable.

Four conceptual configurations were analyzed, with detailed weight and drag analysis results the study's main focus. The final design configuration was a 14,400 lb aircraft with an Aspect Ratio of 5.83 and a wingspan of 38.9 feet. In addition to the rough order of magnitude QFD studies, a model for cost (Eddins Cost Model) was developed and a Taguchi cost analysis completed.

Conceptual design was followed by a preliminary look into the major aspects of design, including airfoil design, structural analysis, engine design, Taguchi weight studies, studies of stability and control, survivability, risk analysis, maintainability, and measures of effectiveness. Finally, a general study of avionics and payload advancements was made to conclude this first design iteration of SEA ARROW Unmanned Armed Reconnaissance Aircraft. Table 6 shows the compliance matrix for the aircraft.

Parameter	RFP Value	SEA ARROW Value
Maximum Flyaway Cost	\$ 8M (2001\$)	\$ 9.5M (2001\$)
Operational Life	50 Missions	50 Missions
Weapons Payload	2000 lbs	1500 lbs
Range ⁽¹⁾	200 NM	930 NM ⁽⁴⁾ , 1603 NM ⁽⁵⁾
Endurance	6 hours on station	7.8 Hours
Instantaneous Turn	28 degrees/sec @ Sea Level	28 deg/sec
Sustained Turn	25 degrees/sec @ Sea Level	25 deg/sec
Alternative Missions	CAS, CAP, SEAD	Yes
Acceleration ⁽²⁾	0.4M to 0.8M ≤ 40 seconds	Yes
Takeoff, Conventional	400 feet	387 feet
Takeoff, Catapult-Assisted	≤ 200 feet	< 200 feet
Signature	Low RCS/IR Signature	4.9 m ² /IR TBD
Specific Excess Power ⁽³⁾	+ 250 fps	> 300 (Clean)
Propulsion	COTS (Commercial Off-the-Shelf)	AE-3007 Variant
Deployment Envelope	4 shipped per C-17	Not Determined
Storage	20 years, (Near FMC)	Not Determined
Manning	Uninhabited Vehicle	Yes

1) Cruise Mach ≥ 0.8 at 30K ft; 2) At 5K feet; 3)At 5K feet ($M \geq 0.4$); 4) Full Ordinance Load; 5) No Ordinance Load

Table 6. Compliance Matrix for Aircraft

3. Payloads and Missions Summary

Although designed for the armed reconnaissance and battlefield interdiction missions, the SEA ARROW can fill many other roles. SEA ARROW is expected to perform Suppression of Enemy Air Defenses (SEAD), Anti-Surface Warfare (ASUW), and specialized Mine Countermeasure (MCM)⁴⁰ missions. It is important to note that the SEA ARROW also has a limited ISR&T capability for operations independent of the Support UAV. The modular payloads⁴¹ envisioned are:

⁴⁰ See CROSSBOW Specialized Supporting Study; “CROSSBOW Mine Countermeasures And Terminal Defense Weapons, by Major Lawrence Lim, SAF, Volume V of this report.

⁴¹ At max fuel load (4300lbs) only 1500lbs of ordnance can be carried; however, at 50% fuel, range still exceeds 400nm and payload can be increased to 3550lbs. Only the 1st three payloads listed were investigated by the Aero design team, the remainder, are payloads SEA ARROW should be able to carry

- 4 x 250lb Small Smart Bombs
- 2 x AMRAAM AIM120 (350lbs ea.)
- 1 x Gun Pod – GPU-2A (M197) (600 lbs)
- 2 x HARM (Inboard ~1000lbs ea.)
- 3 x Jammer pods - new design (Current ALQ-99 ~1000lbs ea.)
- 3 x Anti-Ship Missiles (ASM) Current Air Launched Harpoon
Inboard~1000lbs ea.
- Combinations of three variants of air launched MCM ROVs ~ 500lbs each
- Hunter / Processor / Neutralizer
- Helicopter or ship recovery
- Laser Mine Hunting Module (<2500 lbs)

4. Multi-mission Support UAV

Figure 5 shows a Multi-mission Support UAV.

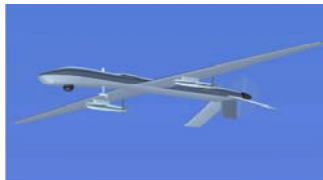


Figure 5. Multi-mission Support UAV

The Multi-mission support UAV was not designed as part of the CROSSBOW project. However, a Specialized Support Study, “Requirements Analysis for an Airborne Communications Node (ACN),”⁴² was completed. The resulting notional CROSSBOW UAV was designed to carry the ACN, Intelligence Surveillance Reconnaissance and Targeting (ISR&T) package, or the Airborne Early Warning modular payload. The design constraints were based on the maximum payload and operational requirements of the three main missions. The CROSSBOW ACN dictated the requirements for maximum payload weight, altitude and endurance and the AEW payload set the maximum power requirements. The CROSSBOW ACN requirements are:

- 12-hour endurance

based on its basic performance characteristics.

⁴²SSS by Major Khee Loon Foo (SAF), Volume V. See also Appendix E .

- Eight hours on station time
- Four hours transit
- Payload of up to 500 lbs
- Launch and recovery from SEA ARCHER

The resulting UAV has a gross weight of about 8300 lbs and a wingspan of about 72 ft.

The Airborne Communications Node is a simple hub in the sky providing theater-wide connectivity to all CROSSBOW forces. Such an airborne node will circumvent most line-of-sight problems and provide an organic asset, which will reduce CROSSBOW dependency on Military Satellite Communications and the associated bandwidth congestion problems. The airborne communications package weighs about 500lbs. This payload can provide a communications relay for VHF, UHF and SHF. As a satellite gateway, the ACN also provides communications beyond line-of-sight to forces outside the CROSSBOW operational envelope. This requires four ACNs flying at 20,000ft launched from SEA ARCHERS. This provides operational coverage over 300nm to all CROSSBOW forces, which include: 64 SEA ARROW UCAVs, 64 Multi-mission UAVs, 20 SEA LANCE II small combatants and the SEA QUIVER Logistics elements.

For the ISR&T mission, the UAV carries a multi-sensor payload that consists of three types of sensors and a Common Data Link. These include an integrated MTI/SAR to take high-resolution pictures and detect moving targets, an EO/IR sensor with laser range designation capability, an Electronic Support Measures payload to detect enemy radar emissions, and a Common Data Link to send near-real-time intelligence back to the ground control station. This combination of active and passive sensors can make the UAV less vulnerable to enemy detection. In an effort to control cost and maintain combat consumability commensurate with the CROSSBOW concept, the payload was designed to achieve a proper balance between cost and performance. The performance of these sensors was based on current sensor technology. With an inventory of 64 UAVs, the synergistic effects of larger numbers and distribution can compensate for the relatively austere performance of the sensors and can allow CROSSBOW to conduct

multiple ISRT missions simultaneously, thus increasing the responsiveness and operational effectiveness of CROSSBOW.

It is recognized that an airborne early warning (AEW) capability is required for CROSSBOW, but time constraints made a detailed investigation impossible. However, a quick-look analysis conducted as part of the “CROSSBOW Air Defense Suite” Specialized Supporting Study⁴³ determined that, with surveillance and detection ranges of 50 nm, it is technically feasible to put an AEW payload on the envisioned Multi-mission Support UAV.

5. Multi-mission Helicopter MH-60

The U.S. Navy is in the process of moving most helicopter missions to the MH-60. Two variants are being fielded, and both can do the armed helicopter missions. For the purposes of the CROSSBOW project, the following missions are envisioned for the MH-60:

- Vertical Onboard Delivery (VOD)
- Combat Search And Rescue (CSAR)
- Anti-submarine Warfare (ASW)
- Airborne Mine Countermeasures (AMCM)
- Anti-surface Warfare (ASUW)

The MH-60 was an obvious choice for CROSSBOW, and since it is a well-understood platform, details of its capabilities will not be repeated here. It should also be noted that no analysis was done as part of this study to determine the appropriate mix of MH-60S and MH-60R airframes. We assumed that eight of each type would be distributed across the eight SEA ARCHERs.

C. SUMMARY OF SEA LANCE II CAPABILITIES & CHARACTERISTICS

1. Background

⁴³ SSS by CPT Sng Chun Hock, SAF. See Appendix H and volume V.

SEA LANCE II is a notional construct based on the NPS Total Ship System Engineering Group's SEA LANCE I design, shown in Figure 6. This ship, designed as a small, diesel-powered inshore combatant, came closer to meeting the CROSSBOW requirements than any other available alternative.

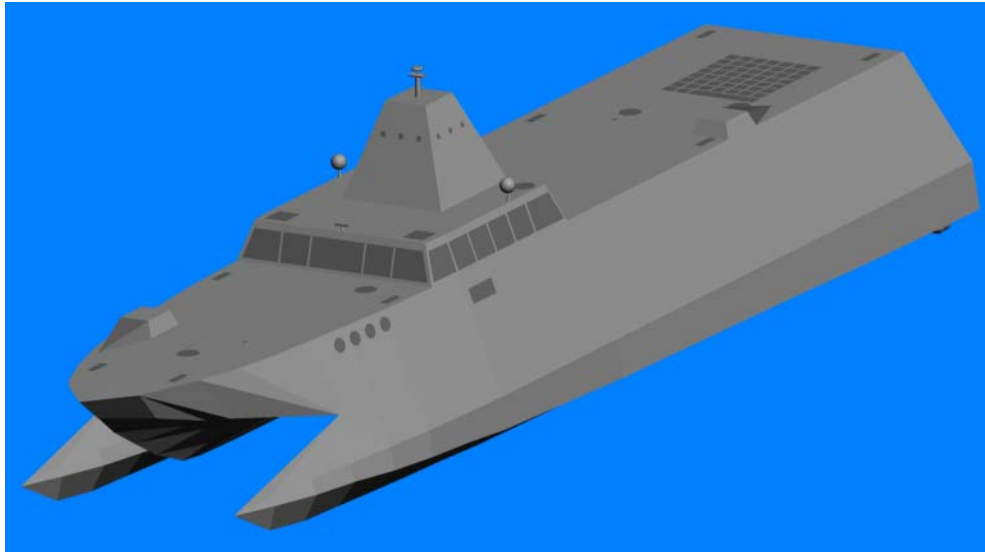


Figure 6. SEA LANCE

However, CROSSBOW speed and endurance requirements precluded using the original SEA LANCE design. Initially the SEA LANCE system was designed to tow a module for the deployment of an Expeditionary Warfare sensor grid. The speed requirement of the CROSSBOW system made transportation of the grid module impractical. We modified SEA LANCE parametrically for the CROSSBOW application. SEA LANCE II is larger than the original SEA LANCE design, with substantially greater fuel storage and propulsion power. We replaced the original SEA LANCE diesel power plant with a gas turbine system as probably the most economical solution to the speed requirements that would also provide for logistic compatibility with the other units of the CROSSBOW force.

2. SEA LANCE II Requirements

SEA LANCE II requirements are as follows:

- Speed: The SEA LANCE II must be capable of operating at speeds commensurate with SEA ARCHER (Threshold: 40-knots transit, 50-knots dash. *We note that since SEA LANCE does not have to launch aircraft, its tactical dash speed is less than that of SEASEA ARCHER.*).
- Endurance: The initial 24-hour SEA LANCE I combat endurance limit created a logistical and operational burden, noted during Campaign Analysis combat engagements. SEA LANCE II combat endurance should be 48-60 hours.
- Fueling: In order to maintain the level of flexibility and endurance desirable in the CROSSBOW force, the SEA LANCE II must be capable of refueling from SEA ARCHER.
- Mine Warfare (MIW): A more robust organic mine detection and avoidance system is essential when operating in mine danger areas. Two MIW Unmanned Underwater Vehicles (UUVs) are included on SEA LANCE II.⁴⁴
- Anti-Submarine Warfare (ASW) Weapons: Without the Sensor Grid, SEA LANCE lacks an offensive ASW capability. Therefore, SEA LANCE II incorporates the Anti-Submarine Rocket (ASROC) system or circa 2020 equivalent. An analysis should be done to determine the appropriate number of launchers, keeping in mind the distributed nature of the CROSSBOW system.

For compactness, the original SEA LANCE design is not summarized here. For ease of reference, the entire NPS SEA LANCE report⁴⁵ has been reproduced in Volume V.

3. Summary of SEA LANCE II

SEA LANCE II is a minimally manned, compact warship designed for maximum flexibility, while providing as much comfort as possible for its highly trained crew. The operations of the entire ship are controlled from a central control station located on the

⁴⁴ See “CROSSBOW Mine Countermeasures and Terminal Defense Weapons,” A CROSSBOW Specialized Supporting Study by Major Lawrence Lim. (Vol. I, Section III – Executive Summary / Vol. V. Complete Study).

⁴⁵ See “Sea Lance” Littoral Warfare Combatant System. Technical Report. Naval Postgraduate School. NPS-ME-01-001.

bridge. There are numerous reasons to locate the crew centrally. Locating crew members' berthing spaces close to their work provides for quick access to battle and watch stations and also limits the amount of CBR protection space. Locating all living accommodations centrally allowed the design team to produce an environment that affords the crew some amenities not normally present on a small combatant, while also maintaining an austere space footprint. The spacious gym and galley areas give the crew ample space to relax and unwind. The habitable space is also designed to accommodate ship riders, such as Fly Away Teams (FATs) for repairs to SEA LANCE II, as well as SEAL teams or an intelligence detachment. The multi-mission space located in the habitable space could be used for any special equipment or compartmentalization required. A schematic of the combatant spaces is presented in Figure 7.

The ship is designed to withstand only moderate damage, but provides an opportunity for the crew to leave the ship rapidly in the event of heavy damage from attack. Two life rafts, located port and starboard in the central control station, can accommodate 25 people each. The Rigid Hull Inflatable Boat (RHIB), located just aft of the habitable spaces on the starboard side, can be accessed directly from the berthing passageway. The RHIB can accommodate all 21 crew members.

The combatant is designed with a robust combat suite to ensure protection for the craft while operating independently. It has four Harpoon/SLAM tubes along the port side, two 30mm guns located fore and aft, and a 51-cell vertical RF/IR guided missile launcher aft. The ship could also perform maritime interdiction (MIO), non-combatant evacuation (NEO), and escort for the CVBGs or (ARGs). It is well suited for combat against the wide range of small surface combatants found in international navies. The sensors suite is capable of operating in a wide range of environments. The air/surface search radar has a range of 54 Nm, while both the infrared search and track and the fire control radar have a range of 20 Nm. The electro-optical suite has a range of ten nm, and the mine-avoidance sonar has a detection range of approximately 350 yards. Additionally, the ship is equipped with an ESM suite and phased array communications antennas. The entire suite is enhanced by the use of an advanced enclosed mast. Reduction in Radar Cross Section (RCS) is achieved by retracting the mast to a 35-foot

height of eye. This position would be used when operating in a high state of emissions control. The mast can be extended 13 feet to a height of eye of 48 feet, thus increasing the IRST detection range to 20 Nm. The mast also has nine phased array antennas (three per face) located around the mast to support the range of communications requirements and large data transfers needed when SEA LANCE II is operating in a Network-Centric environment.

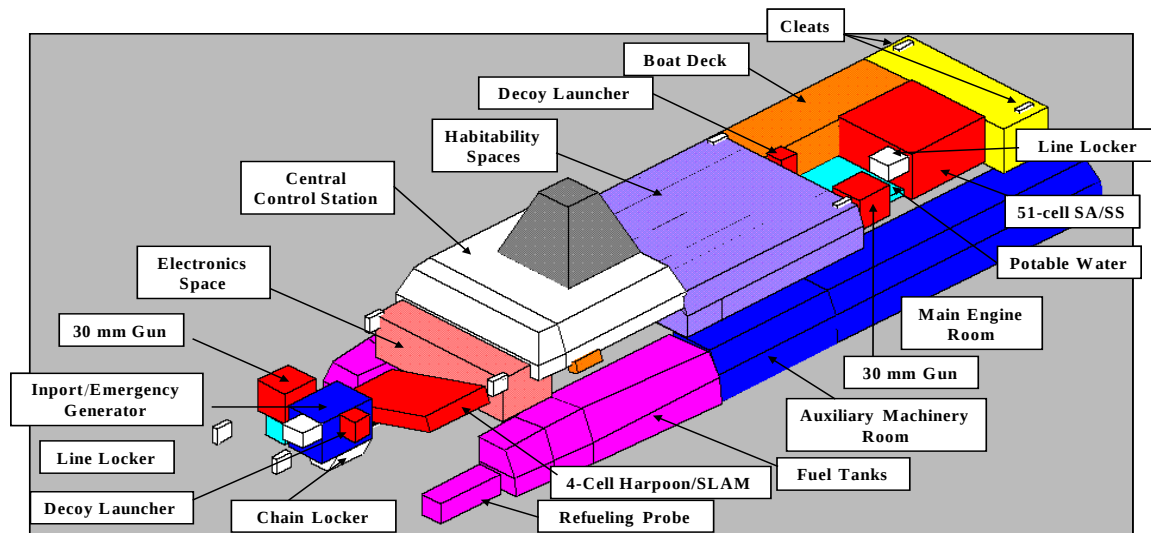


Figure 7. Schematic of the Combatant Spaces

D. SUMMARY OF LOGISTICS FINDINGS

1. Introduction and Purpose

The logistic infrastructure of CROSSBOW has been identified as one of the key factors that will affect the design and performance of a distributed fleet. We strove to identify potential technologies and concepts that could be incorporated into the CROSSBOW system with the aim of reducing the size of the onboard logistics structure and enhancing the support of the system.⁴⁶

⁴⁶ Note that this is a purely conceptual study that is written to serve as the basic framework to support subsequent studies. The study is a combined thesis effort by four Systems Management Officers at the Naval Postgraduate School. In addition to their own curriculum, they participated in many joint courses with the SEI-2 team to develop a suitable and highly integrated logistics concept for CROSSBOW.

The study incorporates these identified technologies into CROSSBOW with the following objectives:

- Increasing operational availability;
- Reducing Total Ownership Costs (TOC);
- Improving operator and equipment safety.

2. Methodology/Approach

The approach was to review current logistic practices and procedures to identify potential areas for improvement. Research, interviews, and site visits were then conducted to identify potential technologies and concepts that could be used to address the areas identified. Subsequently, a framework was devised to functionally integrate the selected technologies, techniques, and methodologies into a feasible architecture. The proposed framework was then validated using software simulation tools and life cycle cost analyses.

3. Results: The Selected Technologies

The identified technologies and concepts are:

- **Autonomic Systems:** Autonomic systems take advantage of advances in information and systems integration technologies to provide accurate and timely information directly from the weapon systems to the battle-space managers. When integrated with Prognostic Health Monitoring System (PMHS), the system will be capable of processing weapon system degradation information and will take the necessary steps to expedite replacement and repair of components.
- **Condition-Based Maintenance (CBM):** CBM exploits advances in sensor technology to accurately detect current system condition and forecast the remaining life of systems and equipment. CBM focuses on doing maintenance only when required, eliminating unnecessary and costly periodic maintenance.

- Serial Number Tracking (SNT): SNT is a management system that enables accurate and reliable tracking of individual in-transit components, usage data, configuration management, and component failure. SNT leverages Automatic Identification Technology (AIT) to allow maintenance, warranty and other data to be stored within the system or component itself, easing the configuration management process.
- Distributed Networks and Intelligent Agents: This exploits advances in computing and artificial intelligence to allow decision making and technical repairs to be performed at a lower level, increasing the operational availability of systems and shortening the mean time to restore the capability of a disabled system. Intelligent agents also facilitate improved forecasting and trend analysis capabilities.
- Single Definition Engineering (SDE): SDE is a control management technique that uses common (open) architectures of specific weapon systems and associated software, thus reducing sparing requirements and life cycle costs.
- Life-time Partnering of Weapon Systems Contractors: Life-time partnering is the negotiation of symbiotic relationships with contractors to provide more efficient support throughout the life of the system.
- Modular Weapon System Design: Modular designs provide easier installation and maintenance, with commensurate Mean Time To Repair (MTTR) reductions.
- Tele-Maintenance: Tele-Maintenance makes use of advances in communication and information technology to enable remote interface with engineering and maintenance expertise to assist in maintenance processes.
- Other Innovations: These include labor-saving innovations such as paint-less technologies and robotics. These technologies will be incorporated into a *proposed logistic framework* with the following five main modules: 1) Logistics; 2) Maintenance; 3) Personnel; 4) Training; and 5) Vendor/Contractor. These five modules operate within a Command, Control,

Communications, Computers and Intelligence (C⁴I) information systems architecture. The Total Asset Visibility (TAV) database provides comprehensive information on all aspects of the battle-space, including weapon system status, personnel status/end strength, situational and casualty reporting, and operational forecasting. The C⁴I system will also house a Decision Support System with links to design reference missions. The logistics framework is depicted in Figure 8.

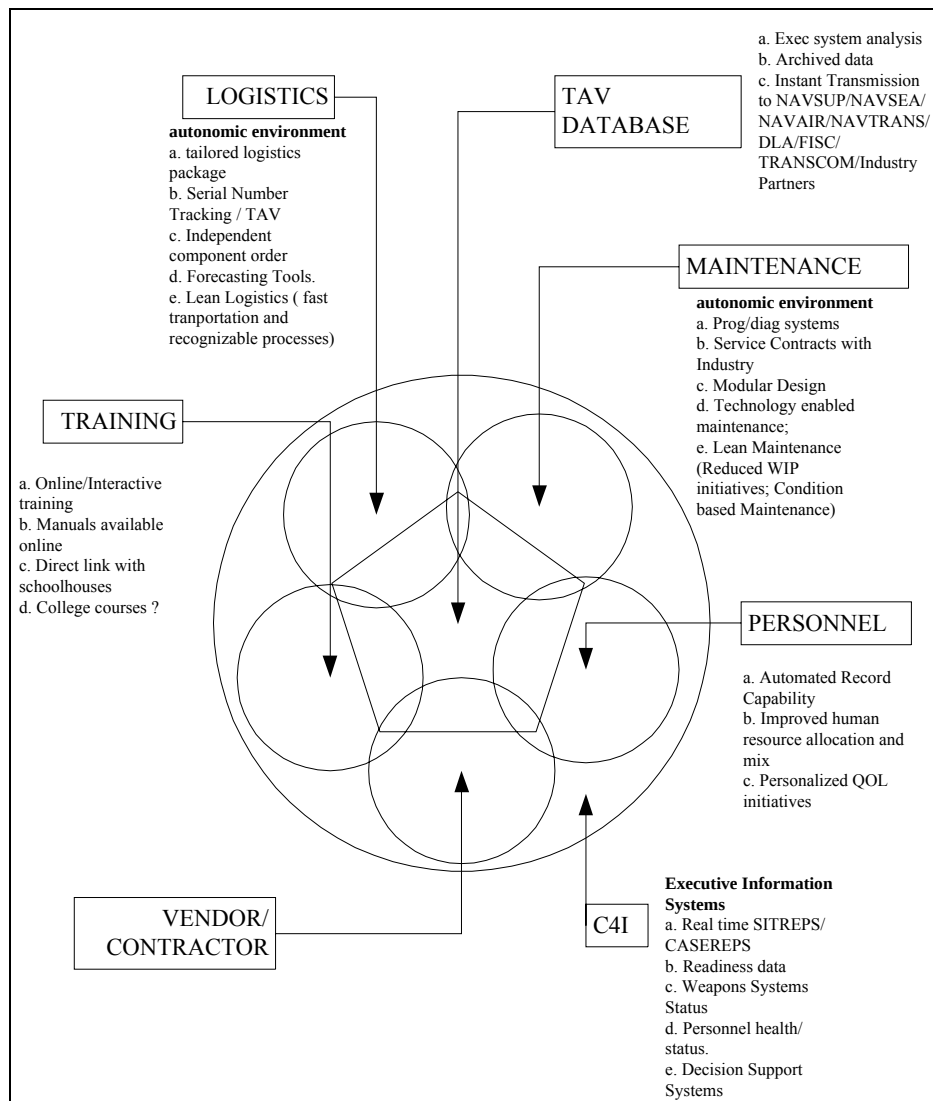


Figure 8. Crossbow Logistics Framework

The various aspects of each of the five main modules are described below.

- **Logistics:** Enhanced configuration management through TAV; manpower and resource reductions through the use of autonomic systems; proactive determination of logistic requirements based upon usage trends and stockroom availability; and improved forecasting tools to improve logistic management and provide faster response to the war fighter's requirements.
- **Autonomic Maintenance Module:** Internal prognostic/diagnostic capabilities within weapon systems to facilitate the maintenance procedure; enhanced forecasting and planning capability for scheduled and unscheduled maintenance activities; online tele-maintenance and virtual technical manuals for improved technical support; recommendations for repair actions when Ready For Installation (RFI) components are not available; and embedded links to vendor/contracted engineering services for support.
- **Personnel & Training Module:** Automated records maintenance and upkeep, including medical, dental, service record, training, pay and promotion documentation; online/interactive training, including *virtual rehearsal* of maintenance procedures.
- **Vendor Contractor:** Real-time links to Prime Contractor to facilitate engineering and technical support.
- **C⁴I Systems:**⁴⁷ The overarching system that links all modules to provide real-time data, anticipatory metrics and a decision support system (with suggested remedies).

The eight selected merging technologies, as presented above and detailed in Volume 5, are critical for reducing manpower requirements, enhancing training, increasing asset visibility, reducing maintenance requirements, decreasing repair cycle time, and increasing operational availability of CROSSBOW. If implemented, they will translate into effective and affordable sustainment of the total weapon system. The

⁴⁷ Please refer to "Logistics and Maintenance Concepts for a Future Naval Force"—by William W. Edge, Joe F. Ray, Gerald P. Raia, and Kenneth J. Brown, Combined Thesis, 2001 Naval Postgraduate School – for an example scenario of how these modules work in tandem. This report may be found in Volume IV.

CROSSBOW sustainment concept provides a general example of an integrated framework with new technologies and methodologies that are obtainable. The reduced training requirement and lower operating hours of unmanned aircraft promise substantial savings in aviation operations such as envisioned for CROSSBOW.

The Navy should not assume that current technologies and methodologies will adequately support the accelerated battlefield tempo and autonomous operations expected in the year 2020 for systems such as CROSSBOW. Given this premise, effort should be expended *now* to conduct analysis, within a Systems Architecture/Engineering methodology, to adapt and integrate new technologies and methodologies to meet the sustainment requirements of the future Naval force.

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IV. CONCLUSIONS AND RECOMMENDATIONS

The CROSSBOW project has given students a rare opportunity to coordinate requirements, conduct tradeoff studies, and function as an integrated and interdisciplinary team. The experience, unique to NPS, has helped students understand the complexities associated with the transformation of technology into a viable future naval force. It also has taught them how to work in interdisciplinary teams to deal with those complexities. This project report is not an authoritative handbook for designing and constructing a distributed force like CROSSBOW. It aims, rather, to highlight the basic concept and what it takes to progress from concept to operational forces. The bottom line is that, although the depth of the study we could undertake does not allow for wholesale endorsement, further investigation definitely is warranted.

A. WHAT WE LEARNED WHILE DEFINING THE CROSSBOW FORCE

- No CROSSBOW force we could conceive is a useful replacement for current aircraft carriers or Carrier Battle Groups (CVBGs). CROSSBOW brings only limited capabilities to blue-water and high-threat areas of operation.
- CROSSBOW can, however, effectively supplement CVBGs in the littorals, providing Theater Commanders with more coverage in low- to medium-threat areas of national interest.
- CROSSBOW can also complement existing U.S. naval forces in high-threat regions, adding robustness and distribution that significantly complicate enemy responses.
- Any force of small, littoral combatants, such as CROSSBOW, must have organic air cover and a viable scouting capability in order to fight effectively and survive.

B. WHAT WE CONCLUDED AFTER DEFINING THE FORCE

- The 60-knot objective imposed on the SEA ARCHER has serious implications for ship design and cost, without commensurate tactical benefit.

- A ship dedicated to UAV operational experimentation would aid in and accelerate development of the technology, tactics and procedures necessary to operate large numbers of sea-based UAVs simultaneously.
- Support of the CROSSBOW force requires enhancements to the existing logistics infrastructure.
- Any distributed force operating independently requires an organic communications relay capability to augment and back up satellite communications.
- High speed, reduced displacement, relatively quiet hull designs, and force distribution significantly reduce CROSSBOW vulnerability to submarine attack. Moreover, a high-speed unmanned airborne ASW barrier, patrolling ahead of the CROSSBOW force, is conceptually feasible and warrants further exploration.

C. RECOMMENDATIONS FOR FURTHER STUDY

This study is not intended to be a “how-to” manual on the construction or configuration of a distributed force. It does, however, provide a basic framework from which to explore and develop the concept further. In particular, CROSSBOW project results strongly suggest the following areas for further study:

- The C4ISR requirement for a distributed force such as CROSSBOW is complex. Due to time and manpower limitations, the study did not cover the subject completely.
- Robust and extensive automation is required to achieve significant manning reductions while maintaining combat effectiveness. This implies up-front investment, including funding development of relevant technologies and full-scale concept definition studies.
- The SEA ARCHER design shows great promise and warrants further iterations, with emphasis on the following: reduced speed requirement, with an examination of the design trade space associated with a 40-50 knot

maximum speed; Cost As an Independent Variable (CAIV); further definition of subsystems associated high-speed flight deck operations, building on design work already accomplished; and further exploration of close-in defense configuration, especially the Rolling Airframe Missile (RAM) launchers. Further iteration of the SEA LANCE II design is also warranted to optimize RAM launcher configuration; provide for launch and recovery of Uninhabited Undersea Vehicles (UUVs); and incorporate Anti-Submarine Rocket capability.

- A more detailed analysis is needed for CROSSBOW air defense, with an emphasis on the technology needed to provide for airborne early warning.
- A second iteration of the Logistic Framework concept is clearly in order and should be closely integrated with the platform and weapons design efforts. Also, there is a need to investigate the desirability and feasibility of a high-speed logistic supply ship—recognizing the danger of its becoming a lucrative target.
- A deeper study of the Network Centric Warfare concept for CROSSBOW is needed, with a view to integration within a distributed fleet. Some of the Specialized Supporting Studies from Volume V of this report could help support such an effort.⁴⁸ Further study of exploiting knowledge processes and artificial intelligence technologies to enhance the information superiority of distributed forces is also needed. Similarly, there is a need to investigate the complex mission planning capability required for multiple simultaneous UAV missions launched from distributed platforms.
- While the CROSSBOW force proposed here is the product of serious analysis and careful deliberation, operational studies to further refine the concept are warranted. In particular, such studies should address the inherent ability of a CROSSBOW force to change in both scale and composition. They should

⁴⁸ In particular, the following studies seem useful: *Requirement Analysis for Airborne Communications Nodes*, *Communications Requirements for CROSSBOW's UAV*, and *An Analysis of Multi Sensor Payloads for CROSSBOW UAV*.

also investigate CROSSBOW operations with combatants of the original SEA LANCE design (SEA LANCE I with the Expeditionary Warfare Grid).

- Operational analyses should further address CROSSBOW operations in conjunction with CVBGs. In particular, they should explore migration of MH-60s and other support aircraft to SEA ARCHER in order to free carrier deck space for strike assets.

D. RECOMMENDATIONS FOR TECHNICAL AND OPERATIONAL DEVELOPMENT

Much of the technology needed to make CROSSBOW an operational reality must be developed. This is true of the operational concepts, as well. However, we assess that most of the technology and all of the operational concepts could be developed by 2012, which could, in turn, lead to an operational deployment of CROSSBOW by 2020. The following are promising areas for technical and operational development:

- Free Electron Lasers show promise for close-in ship defense. This is true for CROSSBOW, as well as for other naval combatants. Development of a ship-based Free Electron Laser should be seriously explored.
- Soft-kill weapons such as directed-effects ElectroMagnetic Pulse (EMP) warheads are a highly promising counter to missile saturation attacks. Soft-kill methods are especially useful for distributed forces such as CROSSBOW. Development of an EMP warhead for the RAM is well worth considering.
- The following operational experiments should be undertaken during SEA ARCHER development and early operational life: high-speed flight deck operations; operations of a CROSSBOW task force with a CVBG; operating CROSSBOW units fully integrated into a CVBG, especially combined operations with manned and unmanned combat vehicles; basing rotary-winged air assets on SEA ARCHER; using SEA ARCHER as a “lily pad” for recovery and staging STOVL strike aircraft and also as a base for those aircraft.

This is not intended to be an exhaustive statement of conclusions and recommendations. Further areas of research and analysis will be identified, and these will lead, in turn, to new conclusions. However, this project report provides a useful reference point for further study of distributed naval forces.

It is worth restating that CROSSBOW is not, and cannot be, a substitute for existing carrier forces. However, we conclude that it has promise to be practical, effective, and affordable. It can fill a specific need for naval presence in low- to moderate-threat littoral regions, supplementing carrier battle groups. Moreover, it brings robustness to the combined naval force, greatly compounding the enemy's problem of area denial against U.S. naval forces, projecting power into high-threat areas. It is also worth restating that limits on time and resources limited the depth of the study.

This study does not provide sufficient depth to endorse the CROSSBOW concept completely. We do find that CROSSBOW is sufficiently meritorious to warrant serious further investigation.

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APPENDICES

In order to further explore the operational and technical feasibility of the CROSSBOW concept, fourteen Specialized Supporting Studies (SSS) were conducted covering weapon systems, communications, information management, automation and logistics. Each student chose their own topic related to CROSSBOW based on individual interests. This division, combined with academic, time and resource constraints, made it impossible to cover all critical areas of CROSSBOW, leaving gaps in the study. Collectively, the SSS represent a first step in the process of examining the key issues and technological options to realize the CROSSBOW concept. There remain other critical areas that warrant further investigation. They include the need to assess the technological feasibility of the physical implementation of Network Centric Warfare, examination of command and control difficulties associated with distributed forces and closer scrutiny of interoperability issues. Presented below are executive summaries of the fourteen SSS. Each summary serves to highlight its respective contribution to the CROSSBOW concept, the methodology employed, the key findings and proposed areas for further research. The complete SSS can be found in Volume V.

APPENDIX A. AN ANALYSIS OF DISTRIBUTED COMBAT SYSTEMS⁴⁹

1. Purpose

This thesis analyzes the potential benefits of a distributed fleet⁵⁰.

2. Methodology/Approach

Campaign analysis techniques and two simple combat models⁵¹ are used to evaluate the performance of a distributed fleet. Additionally, a simple network model is used to evaluate the robustness of a distributed command and control architecture. This thesis also discusses what's needed to support the distributed fleet. Qualitative discussions that incorporate historical lessons form the last part of the analysis.

3. Results

Results obtained from the quantitative analyses indicate that distribution offers the following advantages:

- Increased force effectiveness of a fleet.⁵²
- Flexibility to act in more places at the same time.
- Increased robustness and connectivity with a distributed command and control architecture.
- Denial of enemy opportunity to concentrate its firepower.
- Increased robustness, in that the fleet still maintains a significant portion of its original capabilities even after sustaining predictable losses.
- Increased surveillance activities required by the enemy to detect the entire distributed fleet.

⁴⁹ Based on "An Analysis of Distributed Combat Systems," by Keith Jude Ho. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

⁵⁰ Distribution refers to the allocation of a fixed amount of combat potential among a variable number of platforms.

⁵¹ The Lanchester Equations Model and the Naval Salvo Equations Model.

⁵² In an experiment conducted, it was found that a fleet that has all of its offensive assets on board a few large ships is consistently outperformed by a fleet possessing the same amount of offensive assets but is distributed among many smaller ships.

- Complication of the enemy's information acquisition problem for targeting purposes.
- Avoidance of catastrophic losses associated with the loss of one or two high-value ships.
- Denial of enemy ability to defend with a single maneuver.
- Increased flexibility of fleet composition. Fleet size can be easily scaled up or down to meet the requirements of the mission.
- Increased continuous pressure on the enemy as opposed to "pulsed" operations.

Distribution also allows the fleet the opportunity to employ numerous small ships to carry its firepower. A distributed fleet is then able to exploit the advantages associated with the use of numerous small ships. These advantages include the following:

- Small ships are inherently more defensible by soft kill defenses because of their size.
- Small but powerfully armed ships are suitable for high-risk missions, sanitizing dangerous waters for higher-value ships.
- An increased number of combatants would allow for faster searches and more accurate situational updates.

The benefits of distribution are substantial. However, the logistical, communication, command, and control support required are significantly more complex. A distributed fleet's main advantage lies in its apparent lack of a single point of failure. Hence, the logistical support, communications support, or any other function of the distributed fleet must not turn out to be a single point of failure. Otherwise, the benefits of distribution would be drastically diminished.

APPENDIX B. AN ESTIMATION OF CROSSBOW ACQUISITION AND OPERATING AND SUPPORT COSTS⁵³

1. Purpose

This specialized support study estimates the costs to acquire, operate, and support the entire CROSSBOW force of 30 ships and 144 aircraft. For a distributed concept to be successful, its costs per operational unit must be relatively low.

2. Methodology/Approach

A number of costing models were used to determine these costs. The author created three models to estimate: 1) total Operating and Support (O&S) costs per year by ship type and number of personnel embarked; 2) total acquisition cost for aircraft carriers; and 3) total acquisition cost for ships (other than aircraft carriers). The source data for these models were taken from the Visibility and Management of Operating and Support Cost (VAMOSC) database and the Navy Fact File (NFF). Non-linear regression analysis was used to estimate the cost models.

The aeronautical design team used two established models to estimate acquisition and O&S costs for the SEA ARROW, with a third combination model used for refinement. And lastly, because the author's model for estimating total acquisition costs for ships (other than aircraft carriers) yielded R-squared values less than 80 percent, an established NAVSEA model was used to estimate the costs of the smaller vessel, the SEA LANCE II. In all cases, monetary values were adjusted to FY 2002 using established DoD deflators. Learning curves were not applied to the total costs. Traditionally, learning in ships is quite low, and learning for UAVs has not yet been established, although it is likely to be similar to that of missiles.

Based on the principle of "roughly right rather than precisely wrong," uncertainty is reflected only for "known unknowns." Statistical uncertainty is not included because the statistical models all had very high values of R-squared, except as noted. Finally,

⁵³ Based on "CROSSBOW Cost Estimation", by S. Brent Carroll. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

“unknown unknowns” regarding such questions as operating hours and costs for UCAVs are not addressed.

3. Results

This analysis shows that the entire force of 30 ships and 144 aircraft will cost somewhere between \$9.5 and \$10.9 billion to acquire, and between \$320 and \$350 million per year for O&S. The following is a breakdown of the costs:

- SEA ARCHER. The estimated acquisition cost for each SEA ARCHER is between \$763 million and \$924 million. With eight SEA ARCHERs per squadron, the estimated total acquisition cost is between approximately \$6.1 and \$7.3 billion. The estimated O&S cost is between \$24 million and \$28 million for each ship, while the total for all eight ships is between \$192 million and \$224 million. The wide margin is caused by uncertainty of the cost premium for unconventional hull forms, such as a Surface Effect Ship (SES).
- SEA ARROW. The results of the aeronautical design team's models showed the acquisition cost to be approximately \$10.5 million. The models also provided the breakdown in costs for O&S, which were calculated to be 12.7 percent of LCC, or \$1.8 million per aircraft for 20 years. This is equivalent to approximately \$88,000 per year per aircraft in present day dollars, a surprisingly low figure. Note that these aircraft are unmanned. Finally, there are 64 SEA ARROWs embarked on CROSSBOW for a total acquisition cost of approximately \$672 million per squadron. Also, squadron O&S cost per year will be approximately \$5.6 million.
- SEA QUIVER. SEA QUIVER will cost approximately \$197 million to acquire and \$29 million a year for O&S. Therefore, for two SEA QUIVERs, the total cost per CROSSBOW will be approximately \$394 million for acquisition and approximately \$58 million in O&S costs.
- SEA LANCE II. The estimated acquisition cost for SEA LANCE II ranges from \$72 million to \$80 million. O&S costs for each SEA LANCE II will be

approximately \$1.8 million, and for the entire CROSSBOW squadron, approximately \$36 million. The range in cost is due to uncertainty in the actual displacement of the ship, which is estimated to be somewhere between 550 and 650 Long Tons (LT). Helicopters. The acquisition cost for a SH-60F is approximately \$23 million, and the annual O&S cost is approximately \$1.7 million. Therefore, H-60s for the entire CROSSBOW squadron will cost approximately \$368 million to acquire and approximately \$27 million annually to operate (16 aircraft).

- UAVs. Notional costing for 64 CROSSBOW UAVs, using Predator data, will be \$498 million, or \$7.8 million per copy. This cost includes acquisition and O&S.

The total cost for the entire CROSSBOW appears to be reasonable. Although varying degrees of confidence were achieved with the different models, overall confidence is medium to low because of the immaturity of the concept. It is important to emphasize that a philosophy of “roughly right rather than precisely wrong” was used to ascertain these estimates.

APPENDIX C. AUTOMATED FLIGHT DECK AND AIRCRAFT HANDLING⁵⁴

This section examines the feasibility benefits and costs of automated aircraft and ordnance handling systems. Cost estimates are in 2001 dollars.

1. Why an automated system?

Today's Nimitz class flight deck is manpower-intensive and involves many people working in a fast-moving, hazardous environment. The dangers include jet blast, noxious gases, moving aircraft and other vehicles, jet intakes, excessive noise, bright lights, high winds, and temperature extremes. The risk of accident is ever-present.

During the last eleven years, seventy-five accidents occurred on flight decks in the U.S. Navy, resulting in \$66,271,252 worth of equipment damage and 103 injuries.⁵⁵ While the financial cost of these injuries is unknown, the human cost is substantial. Ninety-three percent of these accidents were attributed to human error.

The annual fully-burdened weighted average cost of compensation per enlisted person on aircraft carriers is \$76,323 (2001 dollars). If aircraft carrier manning is proportional to the number of sorties per day, 226 people will be required for aircraft and ordnance handling and launch and recovery operations, with an annual compensation cost of \$17.2 million.

Both safety and cost considerations warrant exploration of a ship design with an unmanned flight deck. The high ship speeds and resulting high wind over the deck expected on SEA ARCHER suggest that an unmanned system will be required on the flight deck. Additional savings may result from automation of aircraft and ordnance handling.

2. Automated system overview

The system envisioned for SEA ARCHER conducts all movement of aircraft, fueling, storage, ordnance loading, launching, recovering, and mission uploads automatically. Advances in robotics, software engineering, and autonomous guided vehicles will make this possible. Since CROSSBOW is new, design for automation is not

⁵⁴ Based on "Automated **Flight** Deck and Aircraft Handling Feasibility" by Glen Brian Quast. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

⁵⁵ Navy Safety Center Aviation Database NSIRS (One-Liner) 01 Jan 1990 –24 Oct 2001

burdened by the need to work with legacy systems. This system does not control the aircraft in flight or address command and control of the aircraft while not onboard SEA ARCHER.

It is envisioned that the man/machine interface will occur when the Air Tasking Order (ATO) is approved. Once the type of aircraft, mission profile, intended payload or ordnance, and launch and recovery time are determined, minimal human intervention will be required to arm, fuel, move the aircraft within the hangar, raise it to the flight deck, prepare for launch, connect to the catapult, and launch the aircraft. Once the mission is complete, the aircraft lands on deck automatically and is moved to the hangar for preparation for another launch, for de-arming and preparation for storage, or for maintenance.

Fixed wing and rotary wing flight operations will be conducted separately since fixed and rotary wing aircraft require different wind envelopes.

The aircraft will be moved and secured on the flight deck with a system of “TOWBOTS” and on the hangar deck with “TRACKBOTS” and secured in place by “CHOCKBOTS.”

The TRACKBOTS are electric-powered, tracked vehicles that move the aircraft within the hangar where a system of tracks is arranged so that the UAVs and helicopters are moved around without interfering with other parked aircraft. The feasibility of such a tracked system has been investigated using a scale model of the hangar bay, SEA ARROWS, and MH-60s. The aircraft handling system occupies the full width of the hangar bay for 370 feet. Figure 9 depicts the hangar bay and tracked system.

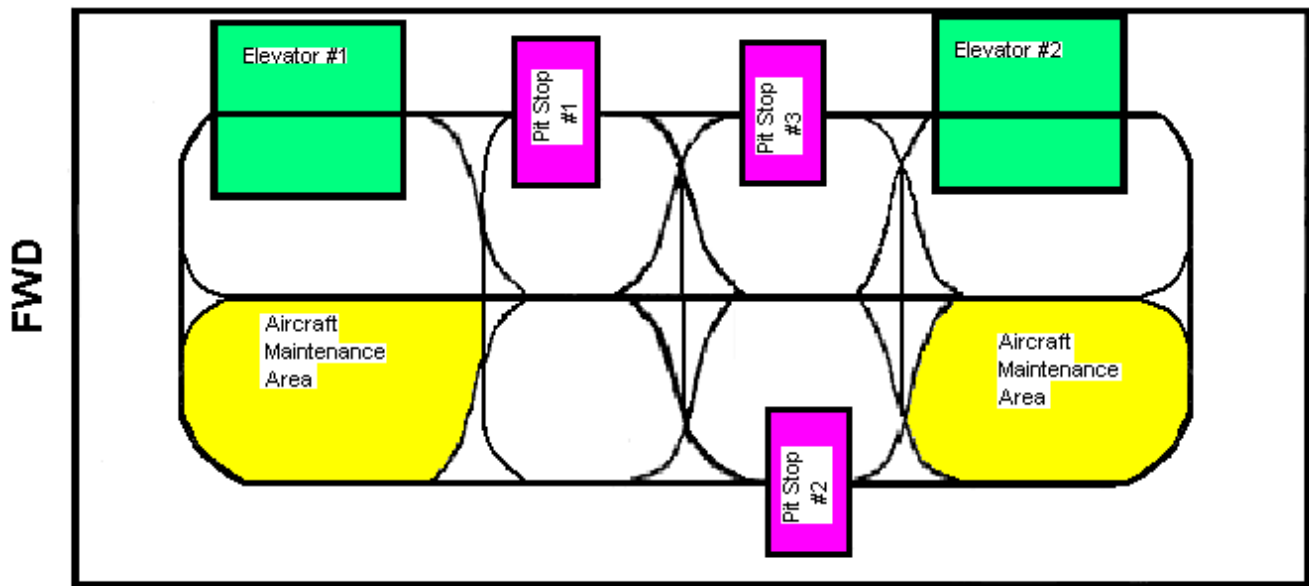


Figure 9. Plan View of Hangar Deck

The TOWBOTs are diesel-powered, infrared-navigated, autonomous vehicles that move the aircraft on the flight deck. The flight deck layout is depicted in Figure 10. The aft elevator raises the aircraft to the flight deck, where TOWBOTs move the aircraft to the launching area. After landing, a TOWBOT connects to the forward landing gear and tows the aircraft to the forward elevator.

The CHOCKBOTs are electric-powered, infrared-navigated, autonomous vehicles that secure the aircraft to the deck in the hangar bay. The CHOCKBOTs automatically connect tie downs to the aircraft main landing gear and the hangar deck once the aircraft is in position in the hangar bay.

4. The cost of an automated system

The initial development and procurement cost is estimated to at \$59 million and the maintenance cost at \$29 million. Even allowing for a significant margin of error, this system is very affordable.

This cost comparison addresses only the difference between a conventionally manned system and the automated system proposed. Benefits of using an automated system, other than cost, will be described in the next section.

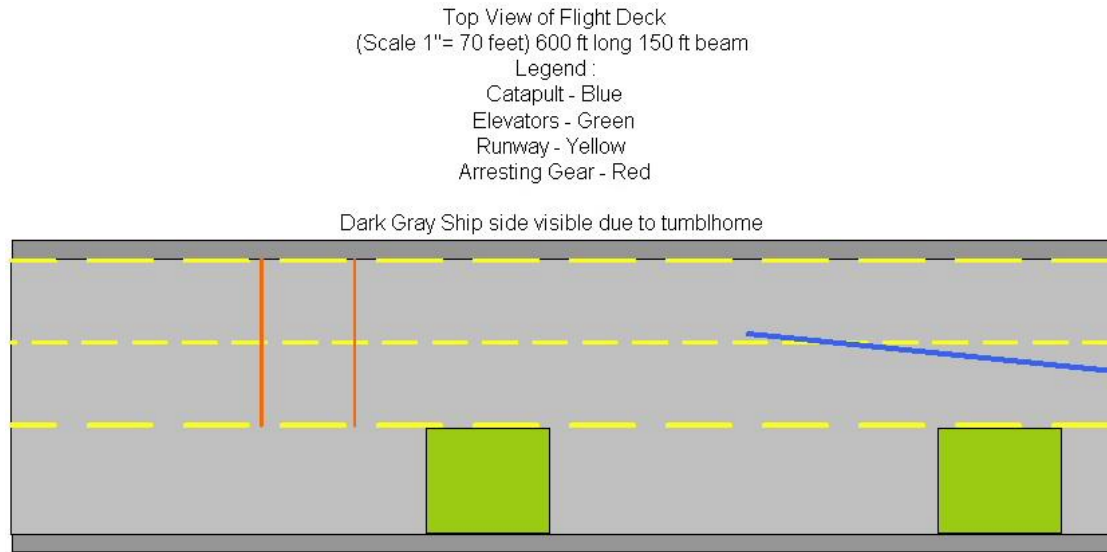


Figure 10. Top View of Flight Deck Test

5. Advantages other than cost

Some of the benefits of operating with an automated system, other than cost, are overall ship design considerations, reduction of human error, and possible Inter-Deployment Training Cycle (IDTC) reductions.

6. Recommendations

The evidence strongly suggests further R&D in unmanned systems for ordnance handling, aircraft movement, fueling, storage, launch, and recovery.

APPENDIX D. AUTOMATED DAMAGE CONTROL FOR REDUCED MANNING FOR FUTURE SHIP DESIGNS⁵⁶

Future ships must be designed with a zero-manning mentality so that each person added must serve a purpose that automated systems cannot provide economically. One of the most difficult automation tasks to envisage is Damage Control, due to its diverse nature, unpredictability, and the agility required for tasks such as pipe-patching, hole-plugging, and shoring. So, although no one envisions a completely unmanned warship, modern and emerging technologies may make significant manpower *reductions* possible. Since Damage Control is an important determinant of overall ship manning, this area has been investigated.

By examining current technologies and making predictions based on test results and technology projections, future ship systems designers can perform functional analyses to determine the best mix of manned and unmanned systems. This section of the CROSSBOW project examines means by which future ship designers could greatly reduce manning levels by utilizing current and projected technologies to automate many Damage Control functions.

Through automation, reduced manning is achievable. Automated Damage Control systems can perform many of the functions currently performed by people, including: 1) heat stress monitoring; 2) fire detection, isolation, and suppression; 3) flooding detection, isolation, and dewatering; 4) electrical fault detection, isolation, and re-routing; 5) video surveillance; and 6) personnel accountability. Additionally, automated systems could decrease the overall reaction/response times through the use of high-speed processing and expert systems.

This section proposes an overarching system, the Integrated Supervisory Control System (ISCS), which could be developed using current technology. If implemented correctly, an ISCS could drastically reduce DC manning requirements and improve

⁵⁶ Based on “Automating Damage Control to Reduce Manning for Future Ship Designs,” by Lance C. Lantier. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

survivability. A major problem inhibiting the development of such a system today is lack of interface and protocol standardization.

Many different elements within the Navy are working on reducing manning through damage control automation, but there are numerous, different, non-interoperable sensors, architectures, and protocols being developed. No project has tested all of the systems required for *integrated* autonomous Damage Control as envisioned in the ISCS. All of the current projects are limited in scope, and even the Naval Research Laboratory's full-scale RT&E mock-ups onboard the ex-USS SHADWELL have not fully integrated all of the systems into an overarching decision and execution system.

A wide variety of sensors and numerous different proprietary protocols and interfaces are being used in the different test projects, but there is no standard protocol in use by all. Therefore, the Office of Naval Research (ONR) projects—in particular, Reduced Ship Crew by Virtual Presence (RSVP) and Network Fragment Healing (NFH)—have parts and pieces that are not directly interoperable with the parts and pieces of other research efforts, such as the Naval Research Laboratory (NRL) Damage Control—Automation for Reduced Manning (DC-ARM) project or the Naval Surface Warfare Center Carderock Division (NSWCCD) Automated Systems Reconfiguration (ASR) project.

Furthermore, the proposed decision systems are incomplete and likewise require both standardization and interface controls. Neither the Damage Control Tactical Management System (DCTMS) software nor the Damage Control Actions Management Systems (DCAMS) software meets all of the requirements to realize an automated DC with reduced manning. The ISCS architecture developed in this section is a first step toward a fully integrated system.

If a design architecture were to be developed with a standardized set of interfaces and protocols for all of the sensors and intelligent agents proposed by ONR, NRL, NSWCCD, NAVSEA and other groups investigating the automated DC problems, one could easily foresee a system much like the ISCS in the not too distant future. System architecture could then be developed from the ground up, using industry standards for interfaces and protocols for all input devices and decision aids.

The Navy and its partners in industry must collaborate to combine technologies in critical areas. For example, the Navy needs to work with leaders in Personal Data Assistant (PDA) technology and Personnel Locator Service (PLS) systems, as well as with medical monitoring device experts. This would enable development of a PDA with PLS functionality, as well as the ability to monitor medical conditions. Water mist systems placed throughout the ship can eliminate manning of fire boundaries, and automated closure technology can eliminate the need for manned material boundary setting. Such systems are clearly feasible, but the cost of hardware, software and maintenance requires careful analysis.

Likewise, acquisition professionals must begin to take a system approach to damage control design and development issues and get involved with their industry counterparts and include them in the ship design process.

In conclusion, there is no part of the ISCS proposed in this section that could not be implemented today if a way could be found to integrate all of the existing, proven technologies into one system with the decision software to support it. The future of reduced manning through automated damage control rests on our ability to do this. If it were successful, the Navy could increase overall ship survivability and reduce damage control manpower and cost.

APPENDIX E. REQUIREMENT ANALYSIS OF AN AIRBORNE COMMUNICATIONS NODE (ACN) IN SUPPORT OF CROSSBOW OPERATIONS⁵⁷

1. Purpose of Research

The fundamental advantage for CROSSBOW as a distributed force is its inherent ability to survive in a moderate- to low-threat environment and provide formidable firepower in the littoral battle-space. While the appeal for operating in a distributed manner is evident, it also has significant potential disadvantages. The complexity of the overall system definitely increases with distributed forces. This, in turn, increases the demand on the Command, Control, Communication, Computer, Intelligence, Surveillance and Reconnaissance (C⁴ISR) systems. Thus, the need for reliable network connectivity becomes even more pivotal. In the absence of a robust network architecture, the operational payoffs of distributed forces cannot be realized. Realizing the significant role that the communications infrastructure will play in the context of CROSSBOW operations, this research investigates the plausibility of employing an airborne communications hub as a method to provide theater-wide connectivity to all CROSSBOW forces via an ACN.

2. Approach

There are, essentially, two major components in the design specification of the CROSSBOW ACN: 1) design specifications of the air vehicle, and 2) design specifications of the communications module.

It is believed that the process of determining the design space of an airborne communications UAV that is capable of launch and recovery from the flight deck of the SEA ARCHER ship is a more technically daunting task than that of developing a modular communications payload. The advent of miniaturization technology in circuit

⁵⁷ Based on “Requirement Analysis for an Airborne Communications Node (ACN)” by Foo Khee Loon. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

board design and VLSI technologies makes the eventual development of the communications payload a relatively simpler task.

Premised on these considerations, we to first define the basic system parameters for the air vehicle and fix its key factors, and then analyze the communications requirements. We size the air vehicle's design space by analysis, using various key constraints. We then compare this space with that available on the SEA ARROW UAV to ascertain if a separate aircraft design is needed. In determining the requirements of the communications module, various link budget analyses, modulation schemes and error correction requirements were studied to identify the general communications system requirements. To facilitate the requirement analysis process, we derived a scaled-down communications model from the existing USN's new aircraft carrier Operational Requirements Document (ORD).

3. Results

Results obtained from the studies above indicate the following preliminary conclusions:

- An ACN UAV carrying a suitable communications payload, flying at 20,000 feet can provide adequate coverage of up to 300nm in diameter.
- The current SEA ARROW design meets many of the ACN UAV's operational requirements. However, it is not an optimized solution from the fuel consumption perspective, having inadequate volume. It is envisaged that the long-term operating and support cost for using the SEA ARROW to conduct ACN operations would not be as cost-effective as a specially designed UAV for the ACN. Hence, we recommend a separate aircraft design. SEA ARROW, with its modular payload bay, can be configured to conduct ACN operations, but this option should be adopted as a contingency—e.g., if all ACN UAV are damaged or non-operational.
- Based on the initial estimates for an aircraft to meet CROSSBOW ACN requirements, (i.e., 12-hour endurance—eight hours on station time and four hours of transit carrying a payload of up to 500 lbs and capable of launch and

recovery from SEA ARCHER), the specialized ACN UAV could have a gross weight of about 8300 lbs and a wingspan of about 72 feet.

- The data link analysis indicates that the proposed communications package for the ACN can provide very superior link quality. The communications module proposed is designed with Binary Phase Shift Key (BPSK), spread spectrum and orthogonal coding scheme. This proposal, while preliminary, shows that jamming protection is possible with the ACN concept. It can provide multiple links to ensure network redundancy and survivability.
- In order to ensure overall network survivability, a minimum of a four-node configuration is proposed. Based on the CROSSBOW force structure of three ACN UAVs per SEA ARCHER, the operational profile of the various ACN configurations is reflected in the Table 7. This template would enable CROSSBOW forces providing continuous coverage for 24 hours a day over a seven-day operation.

ACN per SEA ARCHER	Total ACN Fleet Size	No. of Missions over 7 days	Downtime of 20%	No. of Missions per Day
1	8xUAV	10.5	12.6	1.8
2	16xUAV	5.25	6.312	0.9
3	24xUAV	3.5	4.2	0.6
4	32xUAV	2.62	3.14	0.45

Table 7. Mission Profile for a Four-Node ACN Configuration

4. Follow-up Actions

This research has accomplished a limited feasibility analysis of the ACN concept. Though the technical computations have not been exhaustive, most of the data derived

can be used as a reference model for future detailed design purposes. We propose that, in addition to the communications requirements, the command and control issues for CROSSBOW forces be addressed in depth. The vulnerabilities from operating as a distributed force via an ACN are unclear at this juncture. The overall system level complexity for CROSSBOW forces operating distributed should be investigated in order to better define the command and control mechanisms needed.

APPENDIX F. COMMUNICATION REQUIREMENTS FOR CROSSBOW'S UAV⁵⁸

A key attribute of CROSSBOW is the ability to deploy Unmanned Air Vehicles (UAV) for surveillance and both air-to-air and air-to-ground strike missions. Existing communication schemes for control of UAVs, such as the Predator and Global Hawk, are stovepipe systems and do not address potential interoperability issues when operating a large number of UAVs within a joint naval warfare environment.

1. Purpose

This research paper aims to:

- define the UAV⁵⁹ communication requirements,
- identify existing technological developments that CROSSBOW can use,
- propose a UAV communication architecture for CROSSBOW and
- assess potential limitations of the proposed architecture.

2. Methodology/Approach

The problem was approached first by identifying the functional requirements using the SEA ARROW operational profiles as reference. Research into existing UAV communication-related developments within the DoD was conducted to identify developmental projects that would satisfy CROSSBOW requirements. A communication architecture using existing technology was then proposed. Its feasibility and potential limitations were assessed using communication design principles. The implementation was based on Direct Sequence Spread Spectrum (DSSS) with Binary Phase Shift Keying (BPSK) modulation. In areas where technological solutions were judged not feasible, tactical solutions were proposed.

3. Results

⁵⁸ Based on “Communications Requirements for CROSSBOW’s UAVs”, by Victor Yeo. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

⁵⁹ UAV in this document refers to both ISR UAV and UCAV. UCAV requirements are assumed similar to those of UAVs because of lack of experience with UCAVs to date.

a. Requirements

The fundamental command and control functional requirement of UAVs consists of an uplink and a downlink channel. The uplink channel must be able to send command and control instructions for the maneuver of the UAVs, telling them where to go, what to see or track, and whether to report or fire its ammunition. The downlink channel must be able to provide the operator with the data gathered by the UAVs, whether they are images from the various sensors or its location, altitude, direction, or target track data. Based on the developmental trends, the uplink data rate requirement is expected to be less than or, at worse, equal to the existing 200 kbps rate used by Predator or Global Hawk. The downlink data rate is expected to follow the MPEG 2 compression/transmission standard dictated by the Motion Imagery Standards Profile (MISP) in Joint Technical Architecture (JTA) 4.0.⁶⁰

The functional requirement identified above will require three physical components: 1) a Ground Control Station (GCS) on board SEA ARCHER that will allow the commander to command and control the UAVs; 2) a communication link that can handle the required data rate; and 3) a transceiver unit for both the ship and the UAV. Operationally, each SEA ARCHER must be able to control at least eight UAVs simultaneously. Control of the UAVs must be interchangeable among the SEA ARCHERs when required. Information downlink from the UAVs must be accessible to all surface combatants within CROSSBOW, and it must also be able to hand over UAV control to a land-based GCS for ground support missions.

b. Existing Developments

The command, control and communication of the UAVs in CROSSBOW will have to fall within the Navy's C4ISR vision of Joint and Naval Warfare laid out in the Navy "Copernicus Concept...Forward." This concept goal is the integrated execution of four essential functions of C4I: connectivity; common tactical picture; sensor to shooter; and information warfare. The DoD and the Services initiated two developments to integrate UAV operations with the services joint C4ISR infrastructure. They are the Tactical Control System (TCS) and Tactical Common Data Link (TCDL).

⁶⁰ MPEG 2 requires a transmission bandwidth of 6-8 Mbps for full color motion image at 30

Employment of TCS and TCDL for CROSSBOW's UAV command and control communications must address interoperability issues with existing Navy platforms. The dissemination of UAV collected information to various customers within the DoD will be facilitated through the TCS interfaces.

c. Proposed Communication Architecture

A proposed system architecture using TCS for the GCS and TCDL for the communication link for CROSSBOW UAV command and control communication is shown in Figure 11.

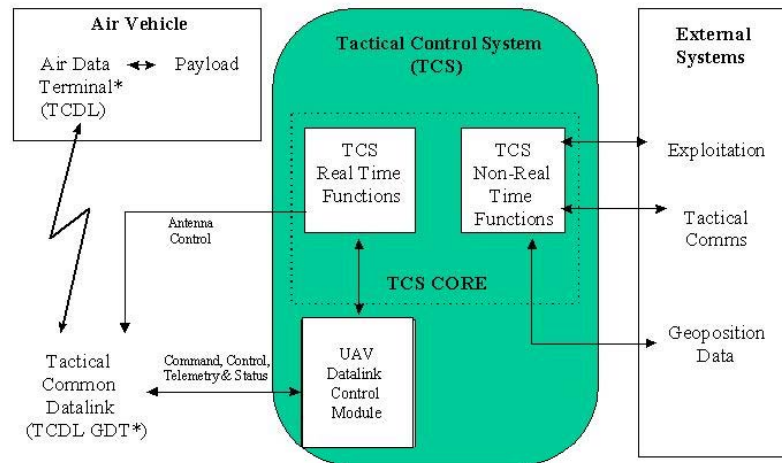


Figure 11. Proposed TCS system Architecture

TCS's ability to command and control the large number of UAVs is largely a function of software and the user interface. These should be easily overcome with increasing processing power and by adding more user terminals. The main limitation is assumed to lie in the communication link.

d. Potential Limitations

TCDL advantages and limitations are investigated through the design of a BPSK spread spectrum with Walsh orthogonal coding and Pseudo-Noise (PN) sequences communication scheme using TCDL. Already allocated bandwidth exists for the projected uplink/downlink data rate, and the existing L3 Communication's Air and Ground Terminal (AGT) serves as our baseline because we have no access to the Navy's scheme due to security reasons. Therefore, the selected communication scheme may or may not be the scheme currently employed by TCDL. From the design and analysis process, the findings are:

- TCDL can support CROSSBOW's UAV communication requirement of 60 UCAVs (assuming 200 Kbps uplink and 2 Mbps downlink) and 20 ISR UAVs (200 Kbps uplink and 10.71 Mbps downlink) simultaneously.
- Number of platforms supportable is dependent on the data rate required.
- Jamming protection of 27 dB to 40 dB is attainable, and jamming beyond 200km is unlikely due to the high power requirement for a fixed jammer.
- Jamming on inland missions is possible when the UAVs fly over land at only 20,000 ft (6 km).
- Operation beyond the 200km range of TCDL will have to be addressed by Airborne Relay Node (ACN).
- Source Routing⁶¹ is required to overcome possible obstruction of the line of sight channel.
- Ku Band SATCOM should be used as a backup to the ACN for redundancy.

⁶¹ Dynamic source routing requires several adjacent links to guarantee the availability of an alternate route. This is accomplished by means of a routing protocol where each radio continuously monitors the adjacent link performance and updates a routing table for a possible network configuration. This operates very much like a typical Wide Area Network (WAN).

4. Conclusions

In conclusion, employment of TCS and TCDL for CROSSBOW's UAV communication will address most of the interoperability issues within a Joint theater-wide operation. The existence of a developed transceiver product in support of TCS and TCDL would cut down developmental time and cost if CROSSBOW were to be implemented.

This study provides the basic command, control and communication design requirements and considerations for CROSSBOW UAVs. These data can be used as a model for further analysis.

APPENDIX G. AN ANALYSIS OF MULTI-SENSOR PAYLOADS FOR THE CROSSBOW UAV⁶²

1. Purpose

The purpose of this study is to propose a baseline multi-sensor payload for the CROSSBOW Intelligence, Surveillance and Reconnaissance (ISR&T) UAV. The multi-sensor payload will comprise the following types of payload:

- Moving Target Indication/Synthetic Aperture Radar (MTI/SAR)
- Electro-Optical/Infrared Sensor (EO/IR)
- Electronic Support Measures (ESM)
- Common Data Link (CDL)

The combination of active and passive sensors can make the CROSSBOW UAV less vulnerable to enemy detection. The UAV can switch between active and passive modes depending upon the level of hostility of the operating environment.

2. Methodology/Approach

The characteristics and performance data of sensors collected from market research were used as data in a decision model that determined the optimal payload configuration based on certain physical and performance constraints. Due to the sensitive nature of certain sensor technology in R&D, the data collected were limited to those sensors that are commercially available and the non-classified specifications of those that are in R&D. Although this may not accurately represent sensor technology in the year 2020, it can be used as a worst-case capability scenario for the CROSSBOW UAV at this time. The physical constraints were imposed by considering a notional CROSSBOW UAV platform. This UAV will be designed to carry the Airborne Communications Network (CAN) payload, the Airborne Early Warning (AEW) payload or the ISR&T payloads. The constraints imposed were based on the maximum requirements by each type of payload. The constraints imposed were:

⁶² Based on “An Analysis of Multi-sensor Payloads for the CROSSBOW UAV,” by Paul Chew. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

- Maximum payload weight - 500 lbs
- Maximum payload volume - 15 ft³
- Maximum electrical power - 2 kilowatts

The performance constraints were based on the sensor's target identification capability and its ability to reject false contacts. These performance measures were represented by utility values derived using the analytical hierarchy process.⁵⁷

Cost was used as a variable to determine a list of multi-sensor payloads that satisfy the constraints imposed on the model. Costs were varied from \$500k to \$5M.

The relationship between the cost of the payload and its identification (ID) value is shown in Figure 12. The ID value is a utility value derived using the analytical hierarchy process, where a pair-wise comparison of the different types of sensors was done to determine their relative performance capability. It represents the ability of the sensor system to identify a target of interest. This is based on the image resolution of the

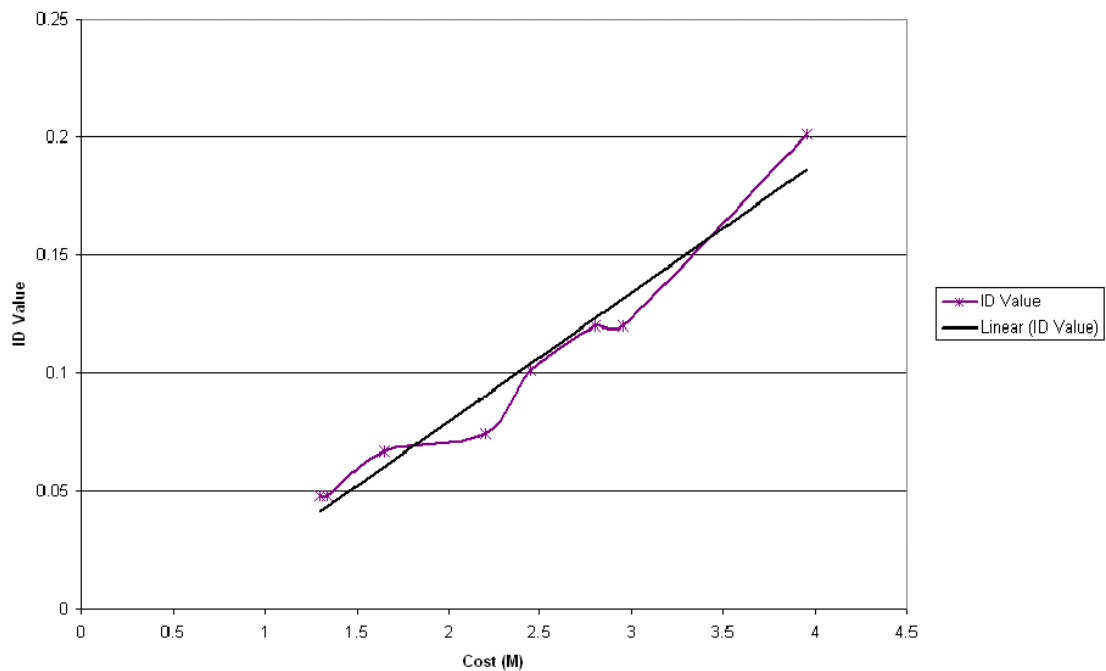


Figure 12. Cost vs. Identification Value

SAR/MTI Radar, EO/IR sensors and the frequency resolution of the ESM sensors. It was found that a positive and roughly proportionate relationship between cost and ID value exists. This relatively linear relationship makes it difficult to identify any region of diminishing utility per dollar. Therefore, a trade-off between cost and performance has to be made to determine the optimum baseline payload.

From the list of payloads derived from the payload selection model, a cost-performance trade-off analysis was conducted to determine the optimum baseline payload for the CROSSBOW UAV. Table 8 illustrates the performance characteristics of the multi-sensor payloads selected from the model.

Cost(M)	Weight (lbs)	EO/IR	MTI/SAR	EO/IR Resolution (Pixels)	EO/IR Performance Value	MTI/SAR (km/m ²)
1.3	168.1	VERS1	NORGM2	256x256, No LRD	1	14
1.34	161.1	FLIR2	NORGM2	256x256 with LRD	3	14
1.65	213.1	FLIR3	NORGM2	640x480 with LRD	5	14
2.2	217.1	VERS1	GENAT	256x256, No LRD	1	23
2.45	302.1	VERS1	RAY1	256x256, No LRD	1	25
2.8	347.1	FLIR3	RAY1	640x480 with LRD	5	25
2.95	361	NORGM3	RAY1	640x480 with LRD	5	25
3.95	347.1	REC1	RAY1	1968x1968 with LRD	9	25

Table 8. Cost vs. Payload Performance Characteristics

The EO/IR and MTI/SAR sensors were represented by the names of their manufacturers.⁵⁸ A numerical value was required for each performance characteristic. The EO/IR resolution was converted to a performance scale of one to nine, with nine given to the best sensor based on its resolution and whether it has a Laser Range Designator (LRD).

The performance values used describe the ability of the sensor payload to identify a target of interest based on its resolution (EO/IR) and maximum detection range for a unit area of target in km/m² (MTI/SAR). An additional consideration was the inclusion of an LRD to provide targeting data and lasing for the missiles fired by the UCAVs or SEA LANCE. For example, in rows seven and eight, the difference in cost of \$1M is attributed to the increase in EO/IR resolution from 640x480 to 1968x1968. It can be seen in this case that there is a weight decrease of about 14 lbs. This opposing trend is due to the way the sensor is manufactured and packaged by Northrop Grumman versus Recon Optical. Another example of performance comparison between rows three, six and seven

shows that, for rows three and six, the main difference in cost of \$1.15M is attributed to the better SAR/MTI payload installed, which gives a better range of target detection capability (14 for row three and 25 for six). With regard to rows six and seven, there are no differences in performance, although there is a difference in cost of \$0.15M. This is due to the different prices given by Northrop Grumman vs FLIR Systems for the EO/IR systems

While it is always tempting to select the best and most expensive payloads, one has to step back and consider the needs of CROSSBOW. One of the key tenets of the CROSSBOW concept is the need to make every force unit as expendable as possible. Expendability would mean lower costs and, more often than not, a less capable system. However, the synergistic effects of larger numbers and distribution can compensate for this lower capability. Since the CDL and ESM payloads were the same for all levels of total cost, only the EO/IR and MTI/SAR payloads were considered for the trade-off analysis. With this mind, the trade-off parameters and weightings used in the analysis are cost-biased, as Table 9 shows.

Parameters	Weighting
Cost	4
Resolution	2
Range/Tgt Size	2
Payload Weight	2
TOTAL	10

Table 9. Trade-off Analysis Parameters and Weightings

3. Results & Conclusions

Table 10 shows the optimum baseline payload from the trade-off analysis.

Cost(M)	Weight (lbs)	Power (W)	Vol (ft ³)	EO/IR	MTI/SAR	ESM	CDL
1.65	213.1	1225	3.357	Star Safire II - FLIR Systems Inc	Army TUAV MMCM MTI/SAR Northrop Grumman	ESP-Avitronics	TCDL - L3 Communication

Table 10. Baseline Multi-Sensor Payload

With a weight of only 213 lbs, the payload takes up less than 50 percent of the maximum payload weight of the notional CROSSBOW UAV. This extra weight allowance can be used to carry additional fuel to extend the range and endurance of the UAV. This is especially advantageous for ISR&T missions, where demands for range and endurance are high.

Compared to the most expensive and most capable payload, this one costs \$2.3M less per payload. It is also lighter by about 135 lbs. With an inventory of 64 UAVs in CROSSBOW, the total saving of \$147.2M is a significant amount. In terms of performance, as shown in Table 7, the optimum SAR/MTI target detection capability is about 60 percent of the most expensive option, and its EO/IR resolution is about three times less. The higher resolution capability for the most expensive option would mean higher bandwidth requirements for data transfer of images. With a large inventory of UAVs, this bandwidth requirement may pose a problem for the common data link and communication nodes. Therefore, the optimum baseline payload strikes a proper balance between cost and performance commensurate to the operational concept of CROSSBOW.

The concept of CROSSBOW as a platform for UAVs and UCAVs will open up new avenues and opportunities for unmanned operations. The more expendable nature of UAVs allows them to be used in hostile environments that are too risky for manned platforms to operate. The ability to operate deeper into hostile territory without expensive equipment and the risk of human casualties will increase the CINC's sphere of influence and help achieve knowledge superiority.

The introduction of CROSSBOW will increase the market for UAVs and their related sensor technologies. Any indication of a sharp increase in demand for UAVs will generate more funding and greater interest in UAV and related technology from the commercial world. History has shown that when such a phenomenon happens, technology responds. A quantum leap in sensor technology may be achieved, thus making the CROSSBOW UAV an even more potent and effective platform.

APPENDIX H. CROSSBOW AIR DEFENSE SUITE⁶³

1. Purpose

The purpose of this document is to propose the air defense suite for CROSSBOW. The study includes threat analysis, concept of air defense operations, evaluation of resource utilization and combat potential. Command and control requirements and advancements in technology are highlighted.

2. Approach

The concept of air defense for CROSSBOW forces is similar to most existing air defense layered concepts, with offensive counter-air as the first layer followed by defensive hard and soft kills in subsequent layers. However, due to the limited firepower and capacity of SEA ARCHER, it is not possible to have a full layered air defense similar to that of a CVBG. Hence, a reduced air defense capability for CROSSBOW forces is proposed.

Though the concept of air defense will be similar whether the CROSSBOW force is in blue waters or fighting in the littorals, the model for both scenarios can be quite different. Figures 13 and 14 show the two proposed models based on the envisaged concept of operations of CROSSBOW forces.

The model of CROSSBOW Air Defense for blue waters can be conceptualized as above. There will be two UAVs for surveillance with a coverage radius of 50 nm at both ends of CROSSBOW forces. The main reasons for having two UAV AEWs are to maintain comprehensive surveillance and for redundancy. There will be two CAPs forward deployed at a maximum of 50 nm away from the CROSSBOW forces.

⁶³ Based on “CROSSBOW Air Defense Suite,” by Sng Chun Hok. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

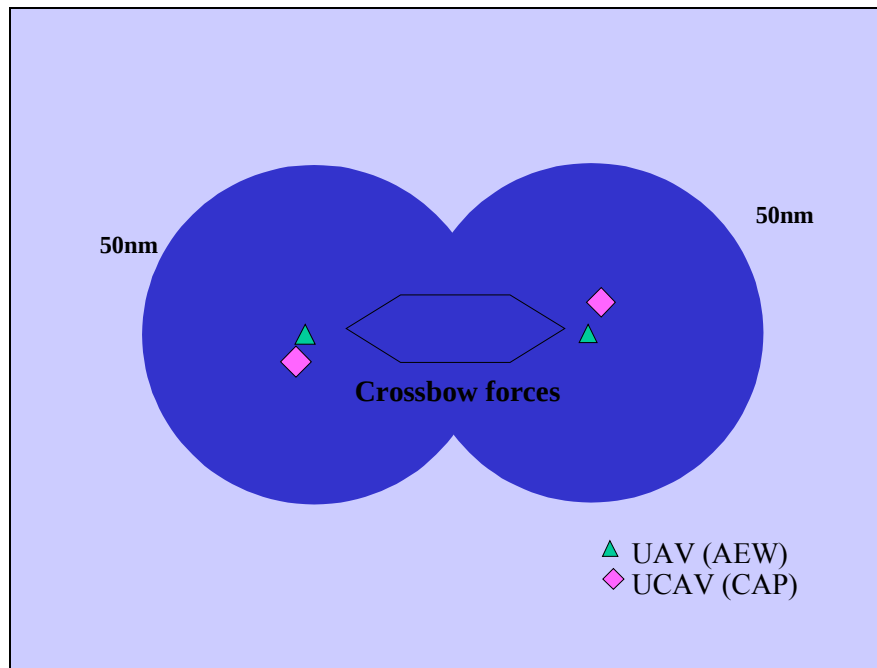


Figure 13. Model of CROSSBOW Air Defense for Blue Water

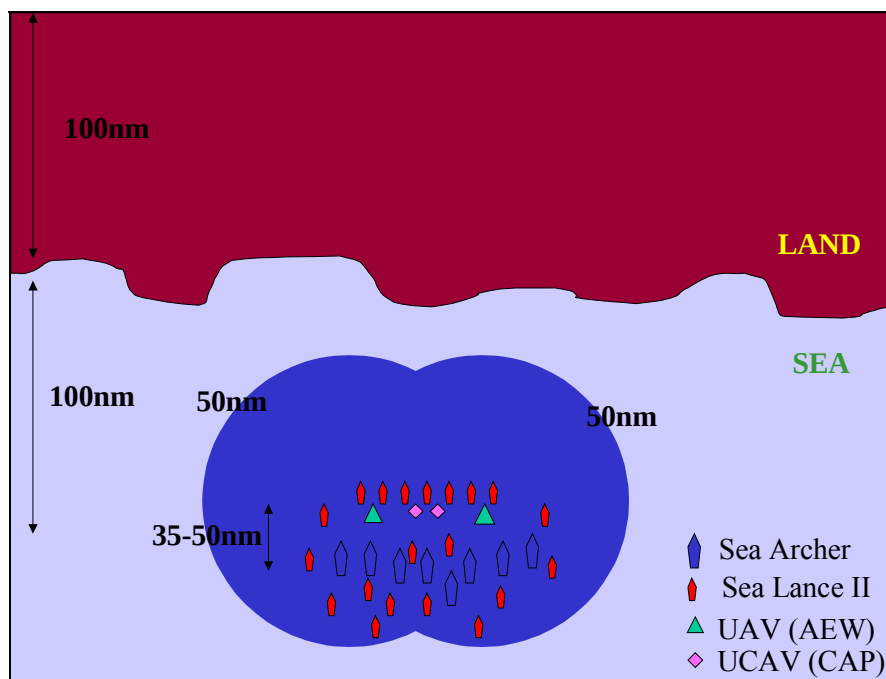


Figure 14. Model of Air Defense for Littorals

Figure 14 shows a tentative concept of operations with CROSSBOW forces operating in the littorals. The SEA ARCHERs are protected by having some SEA LANCEs to the front to absorb enemy fire. The AEW and CAPs will be deployed together with the SEA LANCEs, which are about 35 to 50 nm from the SEA ARCHERs. The SEA ARCHERs are also distributed to make targeting efforts more difficult for the enemy.

The detection ring of 50 nm will give sufficient reaction time for the CAPs to intercept incoming air and surface platforms. A simple calculation shows that, from CAPs position to intercept, a Mach 2.0 aircraft is about 50 nm (based on 35 nm) away from CROSSBOW and from scramble to intercept is about 25 nm. The SEA LANCEs will also assist in destroying the air and surface platforms before they reach the BRL. In addition, the SEA LANCEs will counter sea-skimming missiles launched at CROSSBOW. Any leakages will be countered by other SEA LANCEs (deployed together with the SEA ARCHER), as well as by the last layer of defense using CIWS. It is important to note that sea-skimming missiles can be detected only when they come out of the horizon at about 20 to 30 nm.

3. Results

Preliminary investigation shows that an Airborne Early Warning (AEW) radar with a detection range of 50 nm is sufficient for operations of CROSSBOW forces in both blue water and littoral environments. The 50-nm detection range will provide early warning for one intercept before enemy air platforms reach the Bomb Release Line (BRL). Studies shows that a scaled-down Erieye phased array radar, mounted on a UAV,⁵⁹ with maximum transmission power of 5kW is able to perform the surveillance. The total weight of the AEW UAV is approximately 8500 lbs. A minimum of two AEWs can support most of the defensive requirements of air defense. However, if required, more AEWs can be deployed to provide the necessary coverage. It is recommended that each SEA ARCHER should have two UAVs dedicated to AEW.

Two models that make use of the layered concept of air defense of CROSSBOW are described, one for blue water operation and the other for littoral operation. The key difference between the two models is the disposition of a belt of SEA LANCE IIs to

absorb heavy enemy fire from the land. Both cases show that Combat Air Patrol (CAP) is essential for effective countering of enemy air threats before they reach the BRL. Resource utilization for air defense operation for CROSSBOW forces is also discussed. In short, a minimum of four UAVs for AEW and four to six UCAVs are needed on CAP.

A proposed shipboard sensor suite would consist of the following:

- Multi-function radar (SPY 3)
- Air and surface search radar
- Identification Friend or Foe (IFF) system
- Infra-red search and track system
- Electro-optical system
- Navigation radar
- ESM suite
- Fire control radar

The mast with its capability could be similar to that of the SEA LANCES.

The force application systems are required for the second and third layer of air defenses. The first layer is the use of UAVs and UCAVs for CAP and interception.

The following are some of the last layer of force application systems considered to be on SEA ARCHER and, if possible, on SEA LANCE II:

- Rolling Airframe Missile (RAM)
- Free Electron Laser (FEL)
- Guns

A simple trade-off analysis will be conducted to determine if only one of the systems can be housed in SEA ARCHER or SEA LANCE II, which, of the force application systems mentioned above, will be more suitable in a littoral environment.

CROSSBOW forces (only SEA LANCE IIs) can destroy 38 Anti-Ship Missiles (ASMs) in a time interval of 45 seconds and 77 air platforms in a time interval of 108 seconds before reaching the last line of air defense. The terminal air defense could be a Free Electron Laser (FEL), Rolling Airframe Missile (RAM) and/or guns, as discussed below. Electronic defensive countermeasures are not included in detail because of classification difficulties.

A simple trade-off analysis for terminal defense evaluates three potential configurations: Rolling Airframe Missile (RAM), Free Electron Laser (FEL) and guns (CIWS). FEL is the most effective against increasing future ASM threat. The results indicate that Free Electron Laser is best if only one weapon system can be installed. However, a weapon mix is preferred to ensure that the strengths and weaknesses of the systems complement one another in order to have a more balanced and robust force application system to deal with a greater variety of threats.

Command and control is very important in a sensors-to-shooter environment with friendly and enemy forces operating in the same theater. Requirements for an effective and efficient command and control for air defense operations include a complete air situational picture with large processing capability and an expert system operating within the framework of Network Centric Warfare (NCW) and Cooperative Engagement Capability (CEC). The management of the air defense suite is also very important, and a “Holographic War Room” and a “Timeline Chart” are envisioned to improve reaction and to reduce fratricide.

APPENDIX I. CROSSBOW MINE COUNTERMEASURE AND TERMINAL DEFENSE WEAPONS⁶⁴

1. Purpose

In the present era, maritime mines and Anti-Ship Cruise Missiles (ASCMs) have become readily and cheaply available. They are believed to be the asymmetric weapon-of-choice for an adversary with an anti-access strategy. In order to achieve and maintain assured access to the littorals for expeditionary forces that follow, CROSSBOW combatants must be equipped with effective mine countermeasure and terminal defense weapons. To this end, this study proposes operational concepts and system architectures that will enable the CROSSBOW task force to conduct effective mine countermeasure (MCM) operations and orchestrate an effective defense against a coordinated attack involving multiple Anti-Ship Cruise Missiles (ASCMs) at close ranges.

2. Methodology/Approach

In devising a suitable MCM concept for CROSSBOW, the key operational drivers of successful MCM operations were identified from the U.S. Navy's mine warfare literature and previous CROSSBOW campaign analyses. A technological survey was then conducted to identify the technological opportunities offered by the Navy's ongoing MCM modernization programs and advances in Unmanned Underwater Vehicle (UUV) research and development. Based on the technological survey conducted, the proposed CROSSBOW MCM concept was developed to the level of system architecture by consideration of feasible technological and platform options.

Derivation of the critical operational characteristics of an effective terminal defense system for CROSSBOW was accomplished employing a stochastic model based on the existing Rolling Airframe Missile (RAM) as an investigative tool. The program was developed and coded in MATLAB. Based on the model's response to coordinated attacks involving many ASCMs, a terminal defense concept for CROSSBOW combatants

⁶⁴ Based on "A Concept for CROSSBOW Mine Countermeasure and Terminal Defense Weapons," by Lawrence T.C. Lim. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

is proposed, followed by an analysis of possible weapon options and key enabling technologies required.

3. Results

a. MCM Weapons

In low- to moderate-threat environments, CROSSOW operations are offshore in nature, as there is no requirement to operate within the confines of very shallow areas⁶⁵ (water depths less than 40 ft). Due to the need to arrive swiftly on the scene without being hindered by the threat of maritime mines, CROSSBOW forces must be equipped with organic offshore MCM capabilities. With their small size, low observability, operational flexibility and unique environmental adaptability, UUVs are well poised to play key roles in the CROSSBOW MCM architecture. The envisioned CROSSBOW architecture comprises the following three components:

- Long-range mine reconnaissance UUVs.
- Mine neutralization assets.
- Passive measures.

The long -range mine reconnaissance UUVs are inserted in advance by SEA ARROWS. A reconnaissance package consists of eight mine-hunter UUVs, and four command and control UUVs provide the CROSSBOW task force with the capability to reconnoiter eight channels measuring four miles by 1000 yards. Each reconnaissance package will be launched by at least six SEA ARROWS, with a number of Combat Air Patrol (CAP) SEA ARROWS for protection. Exploiting the intelligence and environmental data collected previously by other Joint and friendly ISR assets, these UUVs have the primary tasks of collecting environmental data, localizing gaps and weaknesses in the enemy's minefields, and transmitting the collected information back to the CROSSBOW task force on transit via the CROSSBOW Airborne Communications Node (ACN) to facilitate follow-on MCM planning.

Based on the intelligence collected, appropriate MCM neutralization assets are then deployed from the SEA ARCHER or SEA LANCE II on transit to

⁶⁵ Based on the world's average, the very shallow water region extends about 600 yards or 530 meters from the beach. The region bounded by the very shallow waters is termed inshore.

reacquire and destroy the mines using the most appropriate neutralization techniques to achieve seamless minefield transit. The CROSSBOW mine neutralization assets are vested in the MH-60 helicopters onboard the SEA ARCHER, which are equipped with a suite of five new organic airborne MCM systems, and two semi-submersible vehicles launched from SEA LANCE II. The semi-submersible vehicles comprise a mine hunter that directs a mine disposal weapon launched from the SEA LANCE II down onto identified mines, as well as a minesweeper

In addition to active MCM measures, passive MCM measures must also be incorporated into the design of individual CROSSBOW combatants. These include the need to control and manage acoustic, magnetic, electric and pressure signatures, as well as leveraging on collected environmental data to optimize routes of passage and enhance the success of MCM operations. The proposed CROSSBOW MCM architecture is summarized in the Figure 15 below.

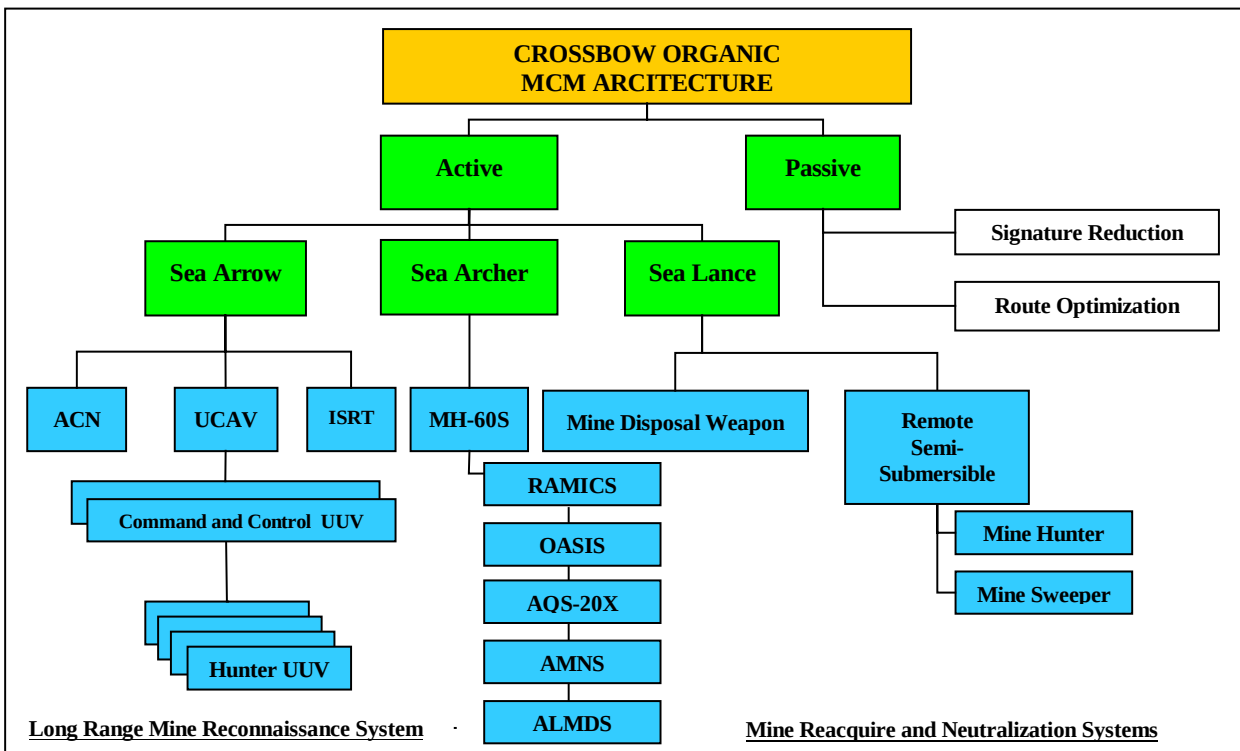


Figure 15. Proposed MCM Architecture for CROSSBOW

Note: RAMICS – Rapid Airborne Mine Clearance System, OASIS – Organic Airborne and Surface Influence Sweep, AMNS – Airborne Mine Neutralization System, ALMDS – Airborne Laser Mine Detection System.

When sustained by the CVBG in a Major Theater War (MTW) scenario, the CROSSBOW task force should also have the capability to perform limited operations against mines and obstacles from the very shallow waters to the beach by deploying inshore MCM weapons such as amphibious UUVs and Hydra-7 munitions. The SEA ARROWS or SEA LANCE II can launch these inshore MCM assets. In this way, more CVBG assets may be made available for other strategic missions that require “longer reaches.”

Some of the key enabling technology issues for the MCM concept are:

- Incorporating the Synthetic Aperture Sonar (SAS) into a miniaturized UUV platform.
- Achieving dense power sources with quiet propulsive trains for UUVs.
- Bestowing UUVs with the ability to communicate and work intelligently as a group.
- Establishing interface standards as enablers of UUV payload modularity.
- Integrating of the various CROSSBOW MCM platforms into a command and control structure that is interoperable with other joint and allied forces.

b. Terminal Defense Weapons

To successfully repel a coordinated attack involving multiple ASCMs from any direction, rapid reaction of the terminal defense system is key. Results from the RAM model indicate that the probability of staging a successful defense is more sensitive to the number of incoming ASCMs than to the engagement ranges. The results establish a need for a terminal defense system comprising small RAM launchers that are suitably designed and distributed around the deck of a CROSSBOW combatant to provide mutually supportive and all-round defensive fires. This would ensure near instantaneous reaction by negating the need to slew individual RAM launchers into firing positions during a multi-directional attack. To establish the trade space for further trade studies, the operational characteristics required of each RAM launcher are summarized in decreasing order of importance in the Table 11.

Importance	Parameter	Requirement	Remarks
1	Reaction Time	Less than 1s	Time required for decision-making, derivation of firing solutions and firing off of the intercept missile from launcher.
2	Circular Error Probable (CEP)	Minimum 0.59m	Determined by the accuracy of the RAM RF/IR guidance system.
3	Flight Velocity	Minimum Mach 4	Ensures at least three intercepts and establishes a 500m buffer zone.
4	Probability of Successful Guidance	0.98	Reliability of the guidance mechanism on the RAM.
	Probability of Track, P_t		Ability of the shipboard radar and RAM RF/IR seeker to track the incoming target.
5	Probability of Detection, P_d	0.90	Requirement is to be able to track many targets simultaneously.

Table 11. Desired Operational Characteristics of a RAM Launcher ranked by degree of importance

The “distributed” RAM system will establish at least three terminal defense layers by firing EMP warheads at incoming ASCMs, engaging them subsequently with hard kill RAM intercepts and denying any leakers a hit by dispensing seduction chaff and IR countermeasures. The first layer is activated whenever the threat of defense saturation is imminent in a particular direction, and the incoming ASCMs can be captured within the effective footprint of an EMP RAM warhead. If the ASCMs are approaching the ship from different directions, hard-kill RAM will be employed from the

onset. Significant technological and engineering challenges are involved in realizing the proposed terminal defense concept. They include the miniaturization of an effective EMP warhead into the RAM, achieving accurate guidance for the RAM at speeds in excess of Mach 4, and engineering a reliable and rapid method of dispensing seduction chaff and IR countermeasures in very compressed times. Based on these considerations, an ideal upgrade to the CROSSBOW terminal defense system is the Free Electron Laser (FEL). However, high power outputs in the mega-watts range would first need to be demonstrated. The conceptual low extraction energy recovery FEL configuration is ideally suited for shipboard applications as it is compact, requires a small aperture for beam focusing and can be powered by small energy devices such as flywheels.

APPENDIX J. HIGH-SPEED ANTI-SUBMARINE WARFARE⁶⁶

1. Purpose

The high speed of the CROSSBOW ships gives them several advantages over slower ships. However, this also presents significant difficulties for Anti-Submarine Warfare (ASW). The ships of the CROSSBOW will travel at speeds up to 60 knots. This speed becomes a factor in these ships' abilities to detect submarines because the faster a ship travels, the more its self-noise will interfere with its sonar's sensitivity. Likewise, flow noise across their sonar arrays will also increase. Once these vessels exceed the breakpoint speed, generally 12-18 knots, this noise will overcome their sonar and they will no longer be able to detect submarines. This could leave CROSSBOW deaf both to the approach of a hostile submarine and to torpedo attack.

The same increase in self-generated machinery and screw noise will also increase the relative detection range at which a hostile submarine is able to locate and track these high-speed vessels. This could increase the CROSSBOW's probability of submarine attack. Therefore, our new high-speed ships will require new technologies and tactics to support high-speed ASW.

This Specialized Supporting Study (SSS) discusses the effects of high speeds on ASW tactics and technologies and suggests new tactics that could support this critical warfare area.

2. Methodology/Approach

This section divides anti-submarine warfare into four key areas:

- Search and detection theory,
- Sensor technology,
- Vulnerability to attack, and
- Offensive capability.

⁶⁶ Based on "High speed anti-submarine warfare," by David E. Bauer. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

Each area is discussed separately to determine how high speeds affect the ability of surface ships to conduct ASW. This section explores potential technologies and suggests alternative methods to conduct ASW while traveling at speeds exceeding 30 knots. It also analyzes the vulnerability of CROSSBOW to a submarine attack and determines the relative advantages, if any, of high speed over the slower speeds of conventional surface ships.

3. Results

a. Search and Detection Theory

It is possible to place a sensor within a manned or unmanned aircraft and use that aircraft to establish a high-speed, moving barrier to patrol ahead of the CROSSBOW. This barrier could then be an effective method of conducting ASW for a high-speed force. This barrier is scalable and dependent upon six key factors:

- CROSSBOW speed,
- Estimated hostile submarine speed,
- Estimated speed of the hostile submarine's torpedoes,
- Estimated range of the hostile submarine's torpedoes,
- Aircraft speed, and
- Sensor capabilities.

Each factor has significant effects on the physical size of the barrier and the amount of resources required to maintain it. The analysis defines the concept of the Submarine Attack Cone of Death (SACD) as a means to relate these factors to the problem. The SACD is then used to determine a Minimum Search Path Length (MSPL) that the airborne searcher is required to follow and the Required Sweep Width (RSW) of the sensor used. The actual technique used in any given situation will be a trade-off between the speed of the vessels involved and the properties of the sensor used. The number of airborne assets required to escort a high-speed task force through a submarine threat area is high. However, the actual number of assets required is feasible, provided that the escorting aircraft have sufficient airspeed, and their sensors have a large sweep

width. The actual calculations and the analysis are discussed at length in the source paper in Volume V.

The question that remains is whether UAVs can support ASW operations. Some research has been conducted but, to date, no published accounts of tasking UAVs with ASW have been published. Most UAVs are designed to accomplish the ISRT mission. This involves cameras or radars as sensors, along with processing and communication equipment to send the collected data back to the ship or ground control station. The task of ASW requires sensors that can detect a submarine. The airframe would need to be large enough to carry one of the ASW sensors. The communication suite would remain essentially the same. The sensors discussed in the previous sections weigh from 100 to 500 pounds and require between two and eight cubic feet of space, depending on the package. Several production UAVs have the capability to carry payloads of this scale.

Additional work must be performed to determine if it is possible to coordinate the operation of several aircraft within the relatively tight confines of the SACD. Likewise, if barrier patrols are to be performed by unmanned aircraft, it is critical that technology be developed to allow them to operate in a succinct and coordinated manner.

b. Sensor Technology

Sensor technology is critical to the success of the type of searches described in this analysis. In order to be useful, the sensors must have the capability to rapidly cover a large volume of search area. They may perform this task individually or in concert with other sensors of the same or different types. Hyper-spectral imagers, lasers, sonobuoys, dipping sonars, and magnetic anomaly detectors are each theoretically capable of performing the task of high-speed ASW, and they may be placed on either manned or unmanned aircraft.

Hyper-Spectral Imaging (HSI) and lasers offer promising capabilities for detecting submarines close to the water's surface under limited circumstances. HSI is limited to daylight, clear sky use only. Lasers are less restrictive. Both are heavily affected by water clarity and sea state. Because of their limitations, additional ASW assets would be required to supplement this equipment. However, it should be noted that

both could serve a dual role in ASW and mine warfare. Further research is required in these fields to determine the specific capabilities of these sensor systems.

Magnetic Anomaly Detection (MAD) is proven technology and will work as long as submarines are produced from ferromagnetic materials. The actual performance capabilities of MAD are classified, but it is likely that the useable sweep width is measured in hundreds of yards rather than thousands. This relatively small sweep width is impractical for the ASW techniques described in this thesis. Therefore, another sensor should be used in tandem with MAD, or MAD should be reserved for localization of submarines rather than for high-speed escort duties.

Sonobuoys and dipping sonar systems still offer the best performance capabilities for detecting submarines. It is theoretically feasible for a group of aircraft to provide an acoustic ASW escort for a group of high-speed vessels. Given the average effective ranges of sonobuoys and active sonar, a flight of four aircraft could provide sufficient coverage for nearly all ship speeds. A field of expendable sonobuoys can be quickly laid down in front of a transiting vessel. However, if the threat region is large, the searcher may quickly expend all of his sonobuoys. For this reason, dipping sonar is more attractive, with the drawback being the need for aircraft that can hover. These systems are currently installed on several manned aircraft. They could also be installed on unmanned aircraft; several Unmanned Aerial Vehicles (UAVs) are sufficient to perform this task. However, no known UAV has been designed to carry sonobuoys or dipping sonar. Further research should be conducted in this area.

The conceptual Expeditionary Sensor Grid (ESG) offers the greatest gain with the fewest assets expended for high-speed ASW. However, the grid must be put into place by some other vessel, which would be vulnerable to attack while placing the grid. Likewise, the actual components of the ESG are still under development, and their performance capabilities are unproven.

c. *The Vulnerability of CROSSBOW to Submarine Attack*

CROSSBOW will have a significantly reduced vulnerability to submarine attack. Specific advantages include reduced radiated noise, a quieter hull and propulsion system design, reduced displacement, and higher speeds. Each of these will make the submarine's target motion analysis very difficult.

d. Offensive Capabilities

The high speed of the CROSSBOW ships will improve the probability of locating a fleeing submarine by minimizing the area in which the submarine can hide. Key factors include the surface vessel's time to arrive on the observed datum and the search speed achieved once on station. CROSSBOW's high speeds will improve the times significantly over slower conventional ships.

4. Summary

This analysis shows that it is theoretically possible to perform a high-speed barrier patrol to escort high-speed vessels through a high submarine-threat region. The task will be difficult, but given today's technology and tactics, it may be the only way to get the job done. The author believes that this analysis shows that further research in this area could prove worthwhile.

APPENDIX K. A CONCEPT FOR IW SUITE IN CROSSBOW⁶⁷

1. Purpose

This study in the area of Information Operations (IO) aims to provide a system-level exploration of the means by which IO can be implemented in the CROSSBOW system. Its objectives are:

- to identify the Information Warfare (IW) requirements of CROSSBOW that could be satisfied by an onboard and independent IW capability
- to define a conceptual IW functional architecture.

The outcome of this effort is the definition of a functional architecture for IW that allows CROSSBOW to perform its missions across all theaters independently or as part of a joint force. The architecture emphasizes interoperability and the use of unmanned vehicles for waging a successful IW campaign. Such a functional description could be used to guide future CROSSBOW research efforts by identifying the areas that must be developed to enable the conceptual IW suite.

2. Methodology/Approach

The study required examination of a relatively new discipline of warfare with a variety of definitions and theories. To keep this problem tractable, the author adopted a Systems Engineering (SE) methodology. The SE method is a structured approach to development that produces a balanced solution to meeting the requirements of the problem at hand. Many references describe various realizations of the SE process. Generally, the process is represented diagrammatically, as shown in Figure 16.

Unlike classical system engineering problems, this conceptual IW suite for CROSSBOW faces uncertainty in end purpose. It is, to some degree, a solution looking for a problem and, thus, is particularly vulnerable to the infamous “error of the third kind,” working on the wrong problem.

⁶⁷ Based on “A Concept for an IW Suite In CROSSBOW,” by Ng Cheow Siang. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

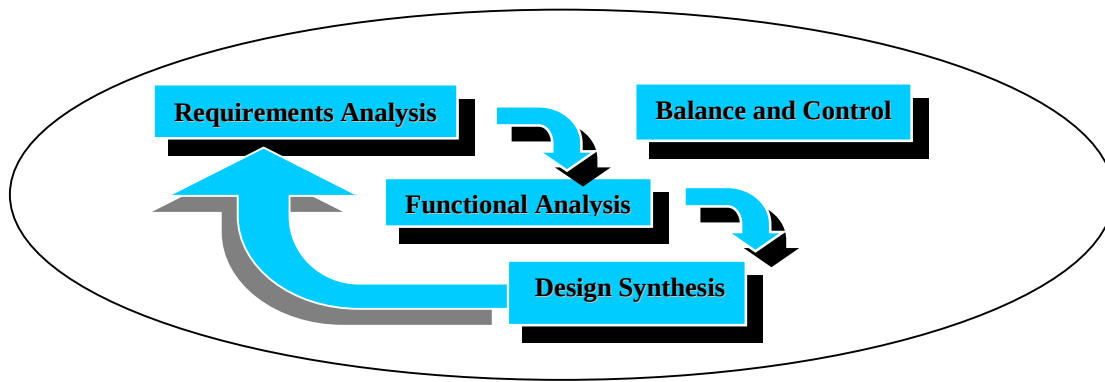


Figure 16. System Engineering Process

3. Concept Development Process

The study proceeded in an iterative manner that focused on finding IW requirements suitable for CROSSBOW. As CROSSBOW is a fighting force spearheaded by unmanned systems (primarily UCAV and UAV), efforts are made to ensure that the requirements can be fulfilled mainly by UCAV and UAVs. Figure 17 shows an overview of the concept development process.

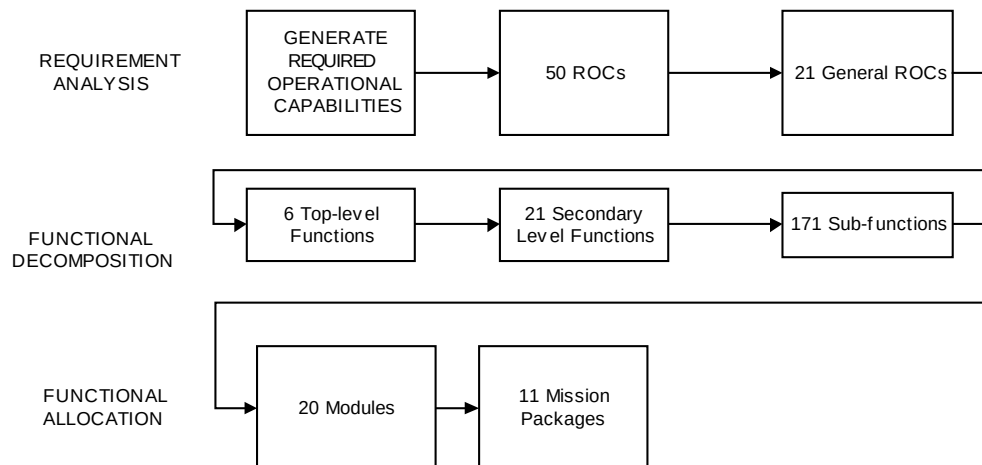
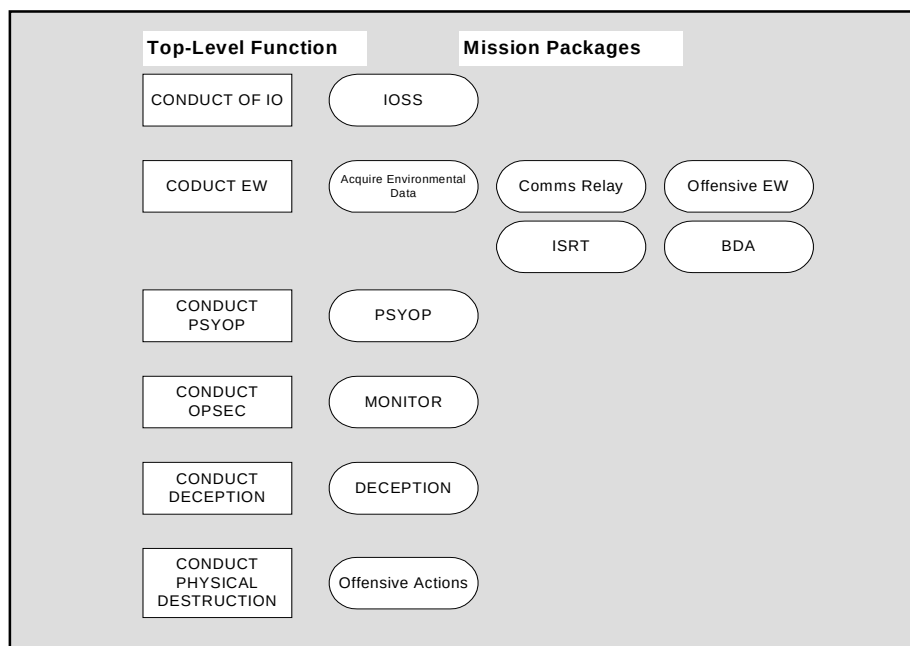


Figure 17. Concept Development Process

Following the SE methodology, the process begins with a requirement analysis to define the set of originating requirements for the conceptual IW suite. Meanwhile, the development of the functional architecture is based on widely published IW literature and an iterative process of comparing the functions with the requirements developed earlier. The result is a functional description of the elements of the conceptual IW suite, in the form of eleven mission packages. They show what each function must do and how each element can be traced back to the original requirement.

4. Results

The conceptual IW suite presented in Figure 18 illustrates the allocation of



mission packages to top-level functions. The decomposition and allocation process revealed that, on the one hand, the “Conduct IO” and “Conduct EW” top-level functions produced the most demand on the mission packages. On the other hand, the other top-level functions produced relatively straightforward mission packages that can be configured with the appropriate technologies.

Figure 18. Conceptual IW Suite Mission Packages

Except for the Information Operations Support System (IOSS), which is on board the CROSSBOW ships and described in detail below, these mission packages can be configured to be loaded on to the UCAV, UAV, or even the MH 60 to be employed in the CROSSBOW system.

a. IOSS Network

The IOSS network is the core of the conceptual IW suite. The network architecture (see Figure 19) partitions IO mission analysis and planning activities from tactical planning and tasking. Operator workstations (clients) coordinate activities on a secure local network that includes three servers:

- Situation Server - maintains a dynamic database of own and enemy force's critical infrastructure and information infrastructure based on current intelligence. Maintains network maps, performance characteristics, vulnerability information, geographic information system (spatial and geophysical maps), and other intelligence data. The associated intelligence workstation performs the automatic correlation of multi-source intelligence to create and maintain the current tactical database regarding the targeted infrastructure (networks, nodes) and situation (perception, infrastructure effectiveness, and functional capability).
- Mission Server - maintains a database of current mission activities, tasking, resource status, and indications and warnings.
- Integrated simulation server - maintains defensive simulations to assess the risk to the group's own information infrastructure. Maintains offensive simulations to analyze tactics, countermeasures, and weapons applied to targeted information networks. The simulations provide performance metrics to quantify the functional effects, collateral damage, and risk associated with information operations.

The system accepts operational orders and intelligence data from higher-level echelons and provides output to flow down operational orders, tasking orders, and intelligence to lower-level echelons.

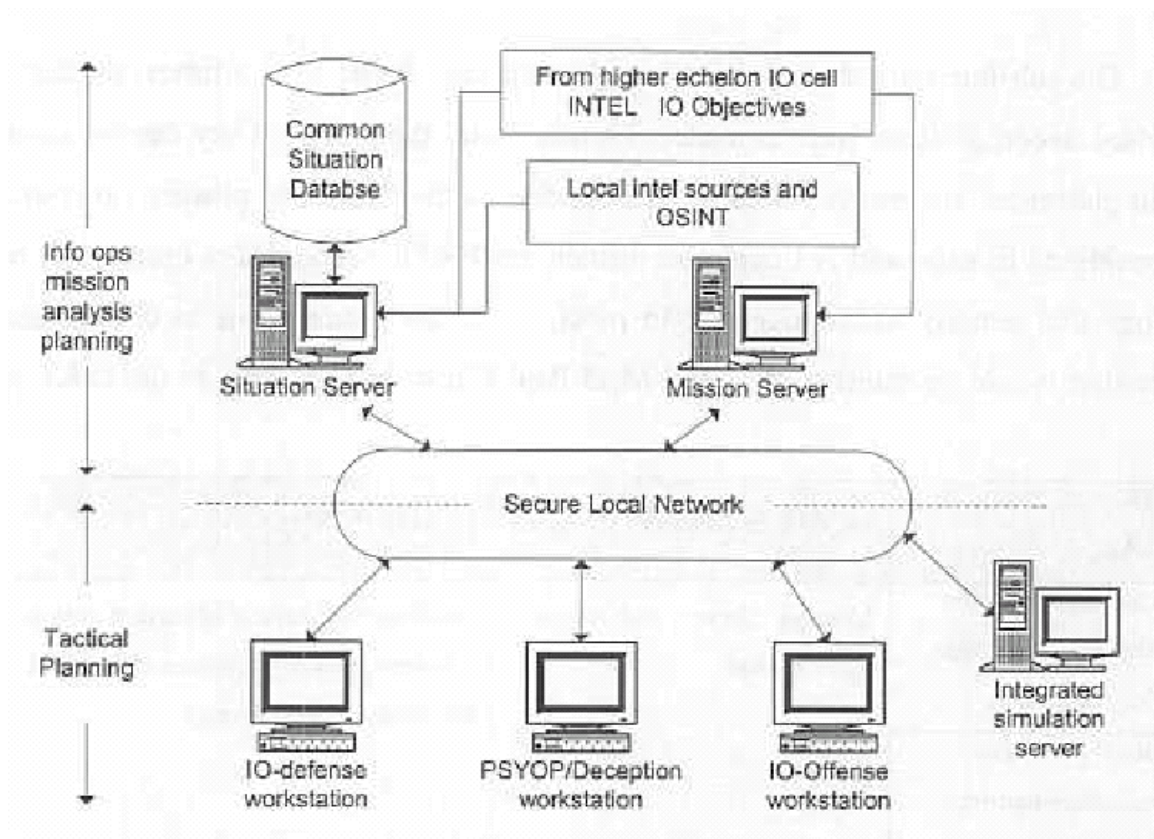


Figure 19. IOSS network configuration

5. Conclusion

This section is an effort to use the system engineering process to bring about a conceptual IW suite. Due to limitations in time and classification of system specifications, the focus was narrowed onto the initial two steps of SE—requirement generation and functional architecting. No physical or technical architecture is specified. In the future, when the CROSSBOW concept is ready to fill a need, the development of technology will have matured, and a more robust physical architecture can then be developed based on the functional architecture.

Inevitably, the selection of functions (and, therefore, the identification of mission packages) is to some extent subjective. Therefore, it is possible that others who perform a similar decomposition analysis could end up with a few more or a few fewer required packages to support the original set of capabilities. Nevertheless, the main conclusion of the analysis is this: an integrated approach to IO can be achieved with relatively small

numbers of computers installed on the CROSSBOW ships and mission payloads installed on a limited number of unmanned platforms. With forward planning, the CROSSBOW is capable of waging a limited IO campaign during its missions to achieve its objectives. Through further investigation, CROSSBOW may become more cost-effective through a balanced mix of IW and conventional capabilities.

APPENDIX L. KNOWLEDGE PROCESS AND SYSTEM DESIGN FOR CROSSBOW ISRT⁶⁸

1. Purpose

Knowledge superiority is envisioned to be a key enabler for future maritime operations. With potentially distributed operations, there is even more reason for the CROSSBOW task force to manage its knowledge effectively and efficiently. This section provides an analysis of a proposed Intelligence, Surveillance, Reconnaissance and Targeting (ISRT) process that could be employed by the CROSSBOW forces. The purpose of this study is to define the requirements for knowledge management and propose the enabling Information Technology (IT) for the CROSSBOW ISRT systems.

2. Methodology/Approach

Future CROSSBOW operations will not be successful without close support from intelligence. The ISRT process will be key in delivering intelligent knowledge to CROSSBOW task forces. Rather than beginning with the design of the supporting IT, an integrated framework for knowledge process and systems design⁶¹ gives a more complete methodology.

The proposed CROSSBOW ISRT process resembles a proposed USMC Reconnaissance, Surveillance and Targeting Acquisition (RSTA) collection cycle of the Marine Expeditionary Force (MEF). First, the proposed ISRT process is modeled and fed into an expert system, KOPeR, for process analysis. The next step is to analyze the knowledge flow within the ISRT process for different instantiations of the ISRT process. Then contextual and information system analysis and system design identify the appropriate enabling information technology for improving the proposed ISRT process for CROSSBOW platforms.

3. Results

a. Modeling the Process

⁶⁸ Based on “Knowledge Process and System Design for CROSSBOW ISRT”, by Daniel Siew Hoi Kok. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

Figure 20 shows the modeling of the proposed ISRT process. The overall commander's intention is translated explicitly and disseminated to the individual commanders in the other CROSSBOW forces. With this "understanding," the individual commanders make better-informed decisions in prosecuting Close Air Support (CAS) and Suppression of Enemy Air Defense (SEAD) missions.

The proposed ISRT process consists of six phases: A) direction, B) planning, C) collection, D) process and produce, E) disseminate and F) revalidation. IT-Support (IT-S) is IT used to convert or transform the input into output. IT-Communication (IT-C) is IT used to communicate or transfer the output. IT-Automation (IT-A) is IT used to automate manual processes. The detailed descriptions of each task and other components of the modeled process are described in Volume 5.

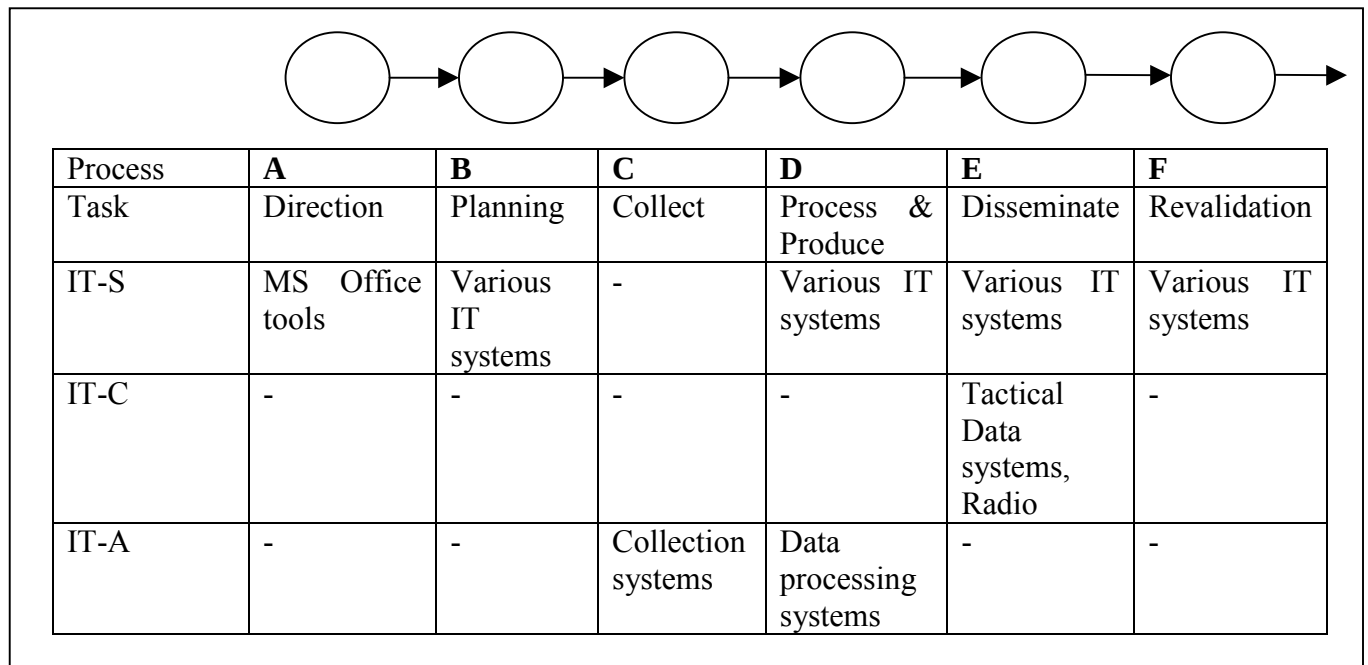


Figure 20. Proposed CROSSBOW ISRT Process

b. Knowledge Management Requirements

Using the integrated framework for knowledge process and system design, four requirements to improve knowledge flow within the CROSSBOW are highlighted:

- A distributed knowledge repository

- Systems that facilitate knowledge exchange
- The need to capture and transfer tacit knowledge
- The proper “pulling” and “pushing” of knowledge

c. *Improved ISRT Process using Enabling Technology*

Based on the KOPeR diagnosis, the author focuses on IT. Although there are several IT systems supporting knowledge management, this study focuses on three of them: 1) knowledge repository, 2) Knowledge-Based Systems (KBS) and 3) Intelligent Agents (IA).

A knowledge repository is a collection of both internal and external knowledge. Informal knowledge repositories seek to capture tacit knowledge that resides in the minds of experts within the organization but has not been put in a structured format. Explicit knowledge has generally been captured in some form that should be filtered, organized and stored in a central knowledge repository. Groupware, as part of a knowledge repository system, refers to software products that provide collaborative support to groups to share opinions, data, information, knowledge and other resources. Through collaboration and discussion, knowledge is evoked, then captured and stored in the knowledge repository. This technology will improve the transfer of tacit knowledge to subordinate commanders. The knowledge repository will also help in better decision-making for subsequent CAS or SEAD missions and for future CROSSBOW deployments. The ability to replicate the knowledge repository is important to the distributed nature of the CROSSBOW task forces. By establishing a proper knowledge repository within the CROSSBOW force, commanders will be able to retrieve important experiences, insight and understanding. Also, implementation of the groupware tool can improve the IT communication in Phases A and E by allowing CROSSBOW commanders to conduct discussions and exchange information and knowledge conveniently.

KBS uses human knowledge captured in a computer to solve problems that ordinarily require human expertise. Well-designed systems imitate the same reasoning process experts use to solve specific problems. Such systems can be used by experts as knowledgeable assistants for improved, consistent results. The interpretation capability of a KBS will help intelligence officers produce the intelligence product during

Phase D. At the same time, the planning capability of the KBS will assist the ISRT group in planning the ISRT mission during Phase B. For both tasks, besides all the operational and doctrinal manuals, the intelligence officers and the ISRT group planning staffs will have to codify and store their knowledge, expertise and experience in the KBS prior to using it. Once operational, the KBS can interact and assist the group in producing the intelligence product and the mission planning. Besides improving the IT support for both Phases B and D, KBS also allows effective dissemination of knowledge to users through an interface. As such, the application of KBS also increases the IT communication for Phases B, D and E. Implementation of the knowledge repository and KBS are not trivial. However, they are proven technologies that have established themselves commercially and that are gaining military acceptance.

Both repository and KBS technologies require users to search through the knowledge repository or database. But in real-time combat situations, time is critical and information overload will be costly. IA are software entities that carry out some operations on behalf of a user or another program, with some degree of independence or autonomy by employing some knowledge or representation of the user's goals. They save time by deciding which information is relevant to the user. With these agents, decision-making ability is enhanced by information rather than paralyzed by too much input, as discussed below.

In finding indications and warnings (I&W) for both CAS and SEAD missions, information must be retrieved from distributed, heterogeneous data sources, correlated and combined, and then evaluated for the likelihood that a threat or target exists. Operators will need intimate knowledge of applicable databases and a significant chunk of time to manually perform the necessary search, analysis and monitoring. CROSSBOW can adopt IA technology to perform the task of identifying and locating CAS and SEAD targets. Once a target is identified, the ISRT group and the CAS/SEAD mission commanders can then task the ISRT UAVs and UCAVs, respectively. Thus, IA technology in this case will improve the IT communication and automation for both Phases D and E.

Figure 21 shows the proposed ISRT process and its implementation using KM systems.

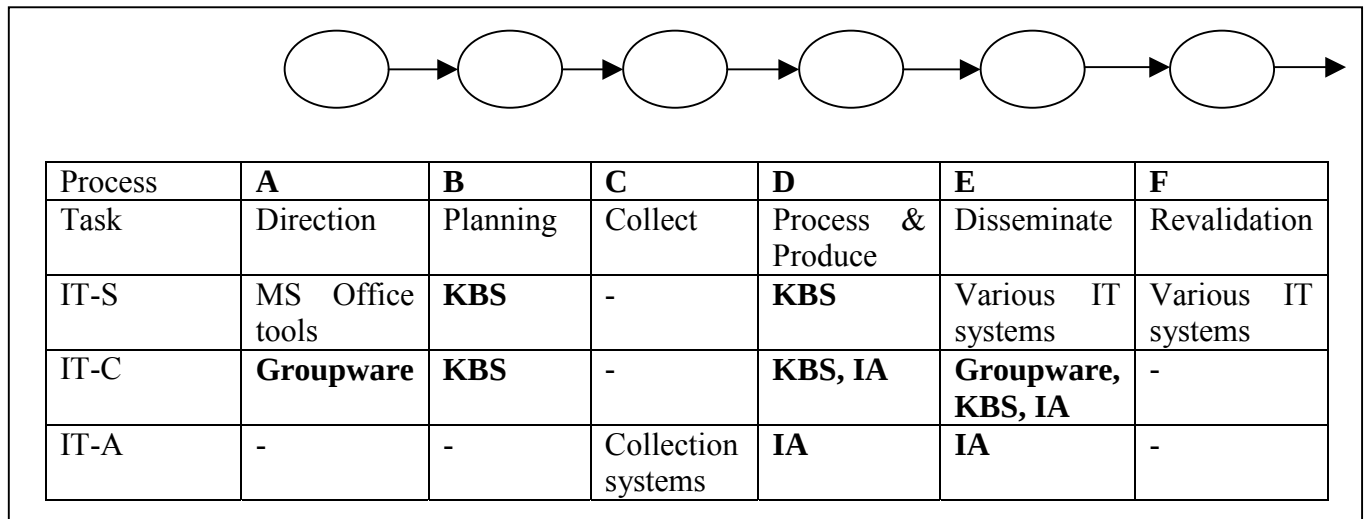


Figure 21. Improved CROSSBOW ISRT Process

APPENDIX M. TRAINING⁶⁹

CROSSBOW is a new concept with operational capability envisioned in 2020. The purpose of this section is to address human engineering issues that can affect manning, training, deployment cycles, and design. CROSSBOW will be on the cutting edge of automation and robotics. Manning will be austere, and intelligent machines will perform many of the tasks now performed by people. This will require crews with a high degree of intelligence and specialized training. The training investment, much of which may be specific to CROSSBOW, may mitigate in favor of a CROSSBOW career path, and a dedicated CROSSBOW community may be appropriate. With eighteen years of deployment lead-time, there is time to re-examine existing manpower and training concepts, and, if necessary, begin with a clean slate. This exploratory study identifies some of the critical training issues raised by CROSSBOW and suggests some directions that may prove fruitful. New training concepts may require significant new infrastructure, so early definition of the manning and training requirements is important.

After identifying unique factors in CROSSBOW manning and training, a number of conclusions were reached:

- CROSSBOW ships should be manned with specialized teams. Emphasis should be placed on determining the best composition of individual skills and redundancy.
- Advancements in simulation and automated technology permits austere manning, but only with capable and well-trained people.
- A dedicated support office is probably necessary to make the concept work.
- New manning concepts could enable CROSSBOW to be on station 18 of 24 months by adjusting the deployment cycle. The crew would report to the ship as an integrated team after a year of specialized training, consisting of three months of individual training followed by three months of team training and ending with six months of individual specialization.
- Deployments of three months would be followed by one month in port.

⁶⁹ Based on “An Exploratory Study of Training Requirements for CROSSBOW,” by Bruce George Schuette. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

In order to implement this training concept, five [you list six] actions need to be taken:

- Crews must be trained as specialized teams.
- Gaming, simulation, and virtual reality must be developed and used.
- New materials must be developed to educate crews and maintain currency in rapidly changing technologies essential to CROSSBOW—e.g., robotics and expert systems.
- Attitude change and team building probably require that some training be conducted underway.
- Passionate dedication to system reliability and maintainability needs to be an important priority to all participants in the CROSSBOW evolution.
- The on-shore infrastructure must be developed that can support CROSSBOW while it is both underway and in port.

It should be emphasized that all of these actions must be taken together in order to get results. One cannot wait to see what is required after CROSSBOW is built. Engineering teams need to design the ships, infrastructure, and human elements concurrently in order to maximize the CROSSBOW potential. This is especially true of the manpower and training programs.

Lastly, today the CROSSBOW training concept is just that—a concept. It needs to become a pilot program that changes and evolves as CROSSBOW evolves. If pursued vigorously, it can lead to formidable training innovations that not only take advantage of the unique aspects of CROSSBOW, but also may have fleet-wide training and support implications.

APPENDIX N. REFUELING ISSUES AND ALTERNATIVES FOR CROSSBOW⁷⁰

This section examines alternative methods for refueling crossbow and estimates the amount of fuel required for a notional mission.

1. Purpose

Current refueling assets and techniques cannot sustain CROSSBOW as it transits at high speed to an area of operations. Moreover, in most scenarios, without prior warning, there will not be enough time to assemble the necessary fuel support. This section addresses this problem.

2. Methodology/Approach

A series of EXCEL spreadsheets were used to predict refueling requirements for CROSSBOW. Amounts of fuel carried, consumed, and needed for refueling are estimated for one specific mission profile. Additionally, research was performed to generate timely alternative methods for delivering the required fuel to CROSSBOW efficiently.

3. Alternatives

This section examines alternative methods and platforms capable of meeting the refueling and re-supply needs of CROSSBOW. These alternatives are named and described briefly as follows:

- SEA QUIVER is a notional Station Ship for CROSSBOW. It needs to transit at an average speed of 40 knots and carry at least 11,000 tons of fuel. In addition to fuel, SEA QUIVER would provide maintenance, a limited range of parts and food, and ammunition.
- The problem presented by refueling a fast naval force is moving large quantities of fuel over long distances quickly enough to meet military deployment and contingency

⁷⁰ Based on “Refueling issues and alternatives for CROSSBOW,” by Paul R. Darling. This specialized supporting study is in Volume V, part 1 of the CROSSBOW Final Report.

needs. Commercial developments of high-speed vessels (HSVs) offer viable alternatives to the traditional ship hull. HSVs operate at greater speeds and more economically than conventionally hulled ships. A bulk fuel carrier HSV, with a cargo capacity of 11,000 tons, would support the CROSSBOW forces at sea and meet the rapid deployment fuel reserve requirements.

- Modern airships provide a fast and economical logistic alternative to conventional shipping. Unlike airplanes and seaplanes, airships rely on an envelope of helium to maintain lift and do not require a prepared landing field when delivering cargo. Also, rough seas do not hamper the airship since it does not “land” on the water. Commercial companies have designs for airships with lifting capacities of over 1,300 tons.
- A proposed use for the aging TRIDENT-class ballistic missile submarines (SSBNs) is to convert them into nuclear-powered guided-missile submarines (SSGN). Another use for these submarines would be to remove the missiles and build fuel tanks inside the missile spaces, thus converting the SSBN into a nuclear-powered submarine tanker (SSTN) with a 323-ton cargo capacity.
- The Mobile Operating Base (MOB) is a self-powered, semi-submersible supply and theater vessel. Modular sections connect serially in order to create an airstrip capable of landing, unloading, and launching conventional fixed-wing aircraft, such as the C-130 and C-17 cargo planes (Zaccola 2000). As conceived, the MOB is better suited than any other ship alternative to realize the at-sea transfer of logistical supplies from tankers and container ships.
- Modularity is an integral part of the CROSSBOW concept. From unmanned aerial vehicles (UAVs) and SEA ARROWs to the internal workings of SEA ARCHER and SEA LANCE II, a modular approach saves time, manpower, weight, and money. If SEA ARCHER and SEA LANCE II are to accommodate modular fuel tanks (MFT) onboard, the initial design must address this requirement. By making the fuel tanks modular, the current method of refueling is replaced by simply switching out one or more tanks. Once the MFT has been emptied, it can simply be removed and slid out

of place using hydraulics and winches, and then a new one can be inserted while at sea. An MFT is designed to hold 110 tons of fuel.

4. Results

Results of the research indicated the following:

- SEA QUIVER offers a viable method for delivering fuel to CROSSBOW and lends itself to the distributed force concept when used as a station ship. A need exists to replenish via a system of shuttle ships or shuttle planes. The AO/AOE, HSV, or airship can meet the shuttle requirement.
- Automated refueling is being explored and would allow reduced manning of future Navy ships.
- Moving cargo across the ocean and around the world quickly via airplanes far exceeds current capability. The use of airships or Wing in Ground Effect vehicles may offer economical alternatives to conventional airplanes.
- In the event that foreign forward basing is not available or adequate, a Mobile Offshore Base offers a technologically feasible alternative, while providing logistical support for forward-deployed ships.

Results of the spreadsheet models indicated the following:

- In order to complete the 15-day mission described in this study, 79,000 tons of fuel are required by CROSSBOW in the area of operation.
- Four SEA QUIVERs, with a cargo fuel capacity of 11,000 tons each, are adequate to meet the transit and on-station mission requirement for fuel.

5. Conclusion

In order to limit the size of the CROSSBOW ships, a ten-percent fuel reserve has been incorporated into the ship designs. We acknowledge that the current standard operating procedure for the U.S. Navy is to refuel at fifty percent, as set forth by fleet

commanders and Operational Orders. Given current technology, we recommend the use of SEA QUIVER to meet the logistical needs of CROSSBOW. In support of SEA QUIVER, the MOB can provide a logistical re-supply base. Airships offer many advantages and may work well as a shuttle ship for SEA QUIVER.

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