The Joint Command and Control Ship (JCC(X)) Approach to Survivability Requirements Development: Total Ship Survivability Assessment

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ABSTRACT

The Mission Need Statement for the Joint Maritime Command and Control Capability requires that the acquired system provide an embarked Joint Force Commander with enhanced mission capability for joint campaign battle management, employ the information superiority gained from advanced Command, Control, Communications, Computer, Intelligence, Surveillance, Reconnaissance, and provide the embarked numbered fleet commander with the same capabilities for operational control of assigned U.S. Navy and allied forces during operations, experiments, and exercises. Survivability requirements and their impact on life-cycle cost, the concept of operations, mission package, and size were recognized as key boundary conditions. To identify and understand the alternatives, a survivability systems engineering assessment was conducted using cost versus effectiveness as a means for comparison of various features including force protection, combat systems, signature reduction, countermeasures, hardening, separation and redundancy, damage control, and firefighting. As a result of this assessment, survivability features were recommended for the Operational Requirements Document that represent a judicious balance of cost versus effectiveness. This article summarizes the approach used and presents unclassified examples to demonstrate the nature of the results. It is intended to be informational for the survivability decision-maker but is not a discussion of current U.S. Navy policy or to be a treatise on terminology or definitions. (Keywords: Joint Command and Control (JCC(X)), Analysis of Alternatives, Survivability, Systems Engineering, Total Ship Survivability, Survivability Requirements Development)

TABLE OF FIGURES

ABBREVIATIONS

ABS	American Bureau of Shipbuilding
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CONOPS	Concept of Operations
DIA	Defense Intelligence Agence
JCC(X)	Joint Command and Control Ship
MNS	Mission Needs Statement
MOE	Measure of Effectiveness
MOP	Measure of Performance
MSC	Military Sealift Command
NAVSEA	Naval Sea Systems Command
NSWC	Naval Surface Warfare Center
ONI	Office of Naval Intelligence
OPSIT	Operational Situation
ORD	Operational Requirement Document
SOLAS	Safety of Life At Sea
TSSA	Total Ship Survivability Assessment
USCG	United States Coast Guard

INTRODUCTION

In a keynote address given to the Air and Space Survivability conference in the Summer of 2000, James F. O'Bryon, Deputy Director, Operational Test and Evaluation, Live Fire Testing, Office of the Secretary of Defense stated that "a vital part of enabling realistic tradeoffs between survivability elements is to embark on the development of a realistic risk-benefit approach that would enable these tradeoffs to be made without prejudice."[1,2] The remark is equally applicable to surface ship and submarine survivability. This Total Ship Survivability Assessment (TSSA) is built upon previous successful survivability systems engineering efforts but has made a significant advance in quantifying operational effectiveness to conduct realistic tradeoffs.

The Mission Need Statement (MNS) for the Joint Maritime Command and Control Capability identifies the need for a sea-based Command, Control, Communications, Computer, Intelligence, Surveillance, Reconnaissance (C4ISR) capability.[3] The MNS did not require or establish specific survivability levels or features. The JCC(X) acquisition budget, at least initially, could not support a robust capability for survivability along with the other critical parameters of speed, joint staff size, and mission package.

The TSSA described in this paper supported the requirements development effort by identifying features, assessing their cost and effectiveness impacts, and using this information to recommend the suite of features which balanced survivability effectiveness per unit cost. These recommended requirements should be included in the Operational Requirements Document (ORD) upon review and concurrence by U.S. Navy leadership. Over the life of the program, the TSSA will provide a survivability decision database for establishing and re-evaluating requirements, for conducting design tradeoffs, for selecting amongst competing proposals, for certifying the selected design by the Naval Sea Systems Command (NAVSEA), and for responding to requests for information by the Fleet during times of hostility or heightened threats.

An afloat C4ISR capability provides the Joint Force Commander a mobile, centralized capability to plan, command, control, coordinate, disseminate, and monitor the decentralized execution of a plan across the entire spectrum of potential military operations during times of peace and hostility. The mobility of the platform provides an inherent level of survivability but additional features were believed necessary. The existing fleet of four command ships (LCC 19, LCC 20, AGF 3 and AGF 11) are nearing the end of their effective service life, do not meet current environmental or habitability standards, and cannot support the payloads required to meet new and emerging missions. Consistent with survivability and mission package needs, it was determined by the program office that commercial standards would be employed for design and construction and due to the potential for manning by Military Sealift Command (MSC), civilian crews would be considered. Concurrent with the TSSA effort, the Analysis of Alternatives (AoA) was being conducted and the results of the TSSA were used as support where relevant and applicable.

A necessary capability of a TSSA is that it allows the survivability decision-maker to evaluate the impacts of a particular feature or suite of features simultaneously for all threats and operational situations.[4] The principle is that a feature that is an absolute best for a particular threat and operational situation might not be best against the range of threats and operational situations it may encounter. The equal consideration of susceptibility, vulnerability, and recoverability features ensures a more robustly survivable design.[5] It also allows the decision makers to consider and ensure that a chosen concept will not fail against any of the likely threats and operational situations it may face within known cost or ship constraints.

This article describes the methodology for the TSSA and uses unclassified examples to demonstrate the type of results. The actual results cannot be included in this article because they are classified. The numbers presented are for illustrative purposes only and do not imply the actual capability of any existing or planned U.S. Navy surface ship or submarine.

The TSSA process followed for the JCC(X) is represented in Figure 1 as an information flow diagram. The foundation of this process for ensuring credible survivability tradeoffs is the identification and usage of a wide variety of threat weapons and accidents and associated operational situations.[6] The process consisted of independent engineering analyses conducted by subject matter experts that were then integrated to support platform level engagement analyses. Due to limited funds and time, campaign and mission level assessments were not conducted. Each engineering analysis considered the capability of the threat weapons in each operational situation and the risk posed to the baseline ship and the reduced level of risk with added suites of survivability features. Where possible, Monte-Carlo techniques were employed to ensure statistically significant estimates. So that cost-effectiveness tradeoffs could be performed on an equal basis, survivability metrics were developed from the engineering analyses, integrated, and plotted on a "Pareto curve" scatter plot for a large number of possible suites. The plots usually exhibited a "knee-of-the-curve" trend which made determining the recommended requirements obvious.

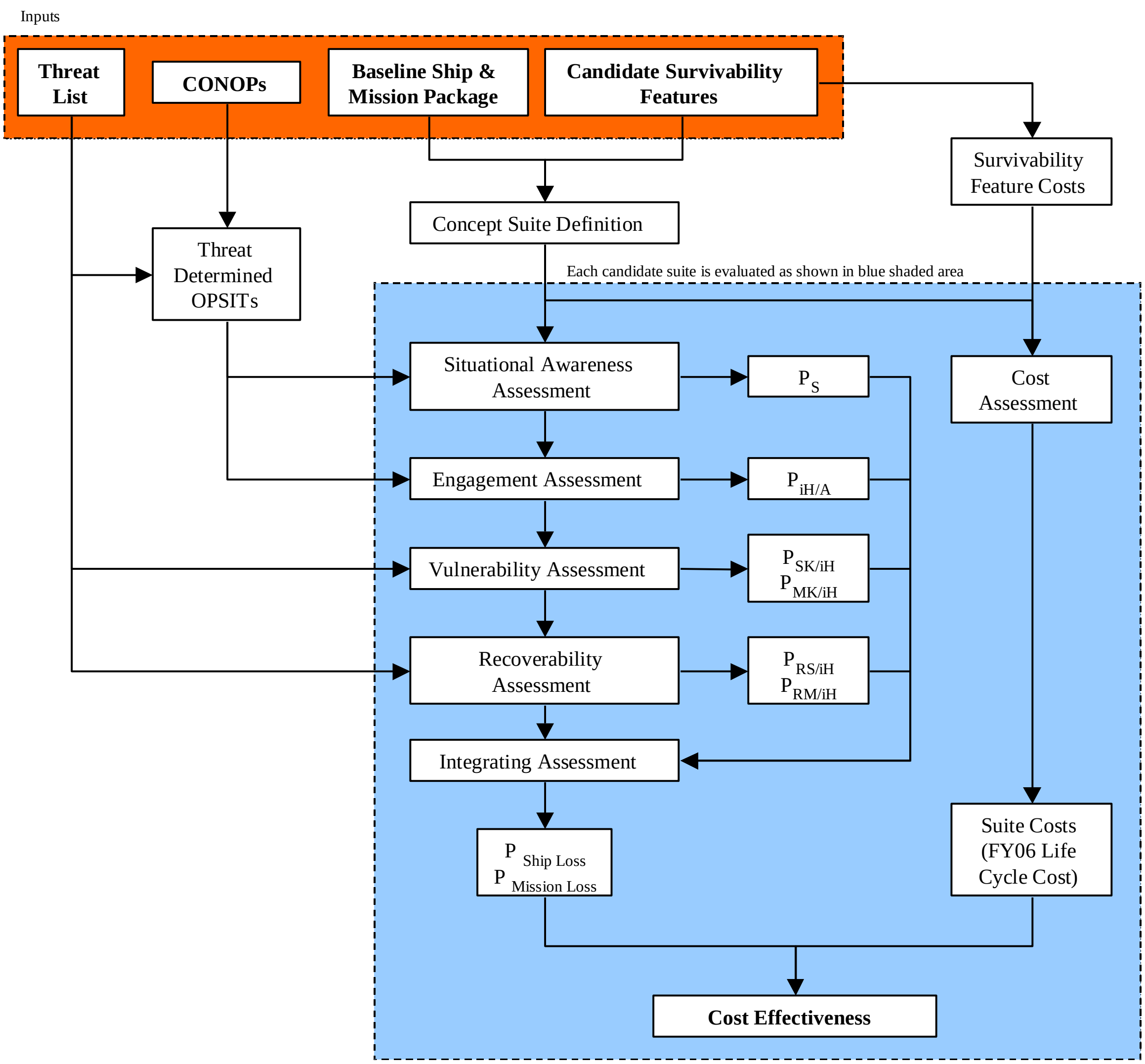

Figure 1. Survivability Information Flow Diagram.

THREAT

The JCC(X) area of operations is considered to be worldwide. Hence, a wide variety of threat weapons and operational situations were required to be addressed. The Program Concept of Operations effort, led by OPNAV N76, was in development concurrently with the TSSA, so threats could not be limited based on expected operating areas or ranges from the shore. Once the necessary data on weapons and operational situations was collected, it was sent to the Office of Naval Intelligence (ONI) for validation by the Defense Intelligence Agency (DIA).[7,8]

The driving philosophy behind threat weapon and operational situation selection was "comprehensive but not exhaustive", which translated to consideration of threats that cover the range of the extremes, but not each and every threat between the extremes. Included in the threat selections were traditional warfare weapon types and associated launch techniques, as well as asymmetric threats and accidents. The accidents addressed in the TSSA were a machinery room fire, a store-room fire, a flight deck fire, and a collision. Operational situations were described to represent threat weapon delivery methods with some consideration for environment, objectives, and tactics over a timeframe suitable for the study objectives.[9]

SURVIVABILITY DESCRIPTION

Survivability is defined as the capability of a system and its crew to avoid or withstand a man-made hostile environment or accident without suffering an abortive impairment of its ability to accomplish its designated mission.[10] Figure 2 shows a survivability functional breakdown of the four component elements: susceptibility shown decomposed as situational awareness and engagement, vulnerability, and recoverability.

Susceptibility is defined as the degree to which a system is open to effective attack due to one or more inherent weaknesses and is a function of operational tactics, countermeasures, probability of enemy fielding a threat, etc…[10] Situational awareness is the capability of the threat country, platforms, and systems to detect, track, classify, and maintain a coherent tactical picture of U.S. Navy platforms, types and locations for the purpose of attacking the platform.[11,12] The engagement phase defines the capability for the threat to achieve some number of hits against the ship, and is conditional upon the threat having successful situational awareness.

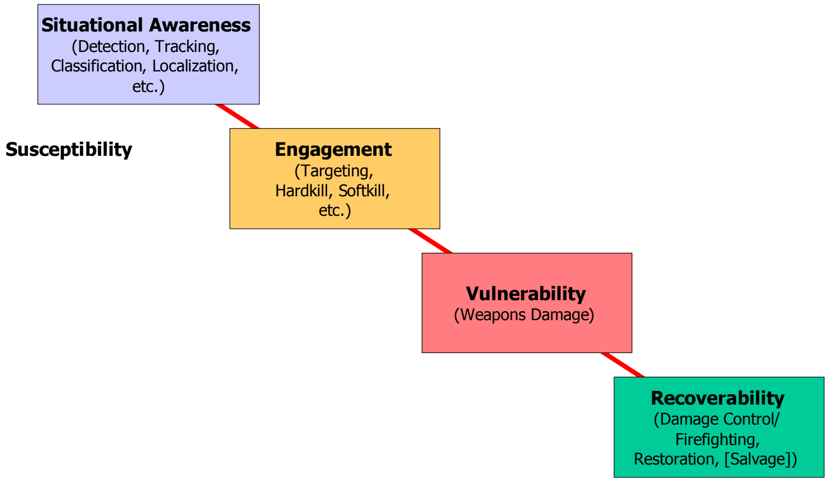

Figure 2. A Functional Breakdown of Survivability

Vulnerability is defined as the characteristics of a system that cause it to suffer a definite degradation (loss or reduction of capability to perform the designated mission) as a result of having been subjected to a certain level of effects in an unnatural hostile environment.[10] The vulnerability phase estimates the expected primary damage caused by a threat type and a given number of hits.

Recoverability was defined to be those actions by the crew, ship systems, other personnel or capabilities, which restore or reconfigure damaged systems to enable the ship to carry out its mission. The recoverability phase estimates the capability to maintain a viable ship given the expected number of hits, likely damage, and damage control and firefighting capability.

FEATURES

The features to be considered and their applicability were identified and filtered based on their current availability or expected development costs. Features expected to have extensive development costs were eliminated from consideration. The resulting list numbered approximately 50 features and was packaged into nine suites of features or survivability concepts. A significant number of the features were not distinct but extensions of another feature adding more of a particular technology.

The baseline concept was defined as a commercial level of survivability in accordance with United States Coast Guard, American Bureau of Shipping, and Safety Of Life At Sea considerations with additional proven, mostly low cost survivability features which in total were estimated to increase procurement cost by approximately 2%. The survivability features included on the baseline, were incorporated because previous independent engineering analyses for JCC(X) had established their cost-effectiveness and because they would fit within the existing guidelines for procurement cost and ship impact. The eight additional concepts employed added a combination of susceptibility reduction, vulnerability reduction, and recoverability enhancing features which resulted in procurement cost increases ranging from 4% to 29%.

During the AoA, the following were considered for the host platform: new designs, modifications of existing designs, conversions of existing vessels and service life extensions of existing command ships. This is an important consideration for survivability feature selection because a significant number of features are not cost-effective for existing ships.

METRICS

With the goal of comparing relative cost-effectiveness, metrics were identified and developed. Most features were not evaluated separately for effectiveness because it was recognized that many would not appreciably contribute without the synergy from other survivability features. Since an evaluation at the mission and campaign level was not conducted, Measures of Force Effectiveness were not quantified. The metrics discussed below are Measures of Effectiveness (MoEs) which focus on the operational impacts at the engagement level and are a mathematical combination of Measures of Performance (MoP) which focus on individual ship characteristics or behavior.[9,13]

The driving philosophy for these was “analytical but not predictive” which means they are meant to support trend analysis consistent with Pre-Systems Acquisition but not meant to imply the level of accuracy required for design and production.[14] The two MoEs used were:

(a) The <u>probability of ship loss</u> (P(ShipLoss)) represents the probability the ship is sunk because of a catastrophic internal detonation, flooding exceeds the floodable length criteria, or the ship is abandoned due to an uncontrolled fire and smoke spread.

(b) The <u>probability of mission loss</u> (P(MissionLoss)) represents the probability that enough of the mission critical systems and compartments were lost due to weapons effects, fire, smoke, or firefighting fluid spread to significantly degrade the C4ISR mission or platform mobility.

The calculation of these metrics was based on the appropriate mathematical combination of the three likely outcomes of a ship concept versus a threat weapon or accident and operational situation. To develop the equations necessary to calculate the three possible outcomes, a decision tree was developed and is shown in Figure 3. Equations 1 and 2 were the result of simplifications to the ideal equations that were developed from the decision tree and were documented in the developmental paper.[15] The three outcomes versus a threat weapon in a specific operational situation that were considered are:

1. Ship Loss and Mission Loss – The ship is lost due to primary or secondary damage incurred during the engagement. This outcome includes cases where the ship sinks quickly due to primary damage, sinks over time due to secondary weapons effects such as progressive flooding, or must be abandoned due to secondary weapon effects such as fire.

2. Ship Survive but Mission Loss – The ship is afloat but unable to complete its primary mission. In most cases this is either because mission critical equipment has been destroyed by weapon effects or the mission spaces have been destroyed by fire, smoke, or water spread.

3. Ship Survive and Mission Survive – The ship is afloat and able to perform its primary mission. This outcome includes cases where the ship is not detected, attacked, or hit, and those cases where the ship takes minor damage from the threats.

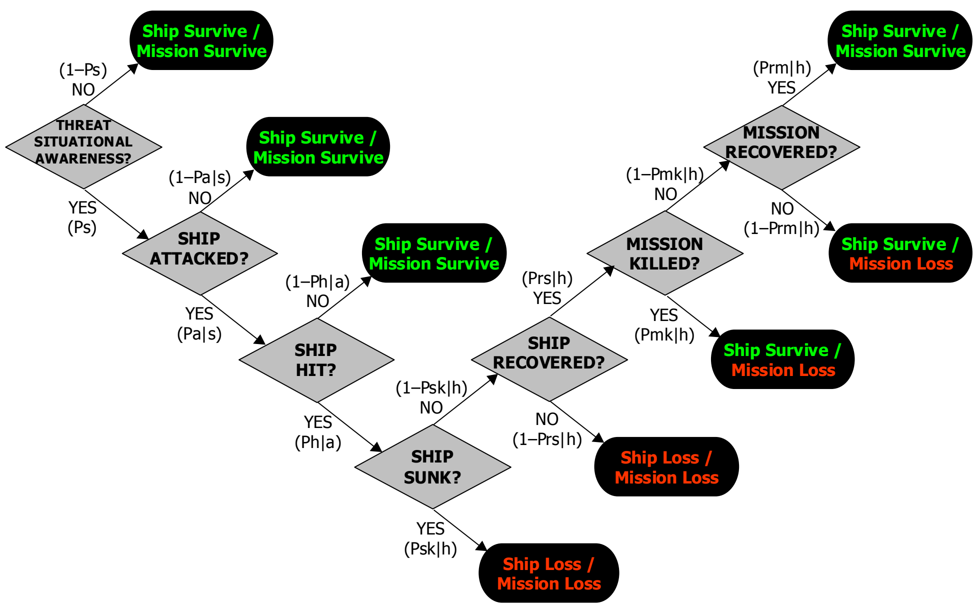

Figure 3: Engagement Level Survivability Decision Tree.

Equation 1.

$$P(ShipLoss) = 1 - P_s P_{a|s} \left[1 - \sum_{i=0}^{i_{max}} P_{ih|a} \left(1 - P_{sk|ih}\right) P_{rs|ih} \right]$$

Equation 2.

$$P(MissionLoss) = 1 - P_s P_{a|s} \left[1 - \sum_{i=0}^{i_{max}} P_{ih|a} P_{rs|ih} \left(1 - P_{mk|ih}\right) P_{rm|ih} \right]$$

where:

- P_s = Probability of successful detection, track, classification, and maintaining track on ship in a given operational situation with specific threats
- $P_{a|s}$ = Probability of attack, given ship is successfully detected, tracked, classified, and maintained in threat tactical picture
- i = Number of hits
- i_{max} = Maximum possible number of hits
- $P_{ih|a}$ = Probability of i hits, given attack
- $P_{sk|ih}$ = Probability of ship loss due to primary weapons effects, given i hits
- $P_{rs|ih}$ = Probability of ship recovery given i hits (i.e., ship is not lost to secondary weapon effects)
- $P_{mk|ih}$ = Probability of mission loss due to primary weapons effects, given i hits
- $P_{rm|ih}$ = Probability of mission recovery, given i hits (i.e., mission capability is not lost to secondary weapon effects)

For the TSSA, the probability of attack was assumed to be 1.0 using the simplifying assumption that if an adversary had identified the JCC(X) as a target, they would attack. To be zero would not require any assessment.

RESULTS

When we plot survivability cost versus effectiveness for a variety of features and suites as a function of the threats and operational situations, we can identify those that provide the most benefit for a unit cost. These selected suites or features are known as Pareto optimal. That is, for a given cost, there is no more effective suite or for a given effectiveness, there is no suite less costly. An additional goal of the TSSA is to ensure that a ship is not procured which is highly survivable against a specific threat in a specific operational situation, but rather one that has a robust level of survivability across the spectrum of threats and operational situations within known cost and ship impact constraints.

By combining this methodology and scatter plot visualization, we have a survivability decision database with which the future decision-maker can make allocation decisions for requirements, conduct design tradeoffs, down-select competing proposals, certify acquired system, or re-evaluate previous decisions against new information including budgetary, schedule, doctrinal, or systemic changes.

The actual results cannot be included in this article because they are classified. The numbers presented are for illustrative purposes only and do not imply the actual capability of any existing or planned U.S. Navy surface ship or submarine.

RESULTS: Situational Awareness Assessment

Situational awareness is the representation of the battlespace and involves data management to produce the essential information in a usable form on which the warfighter can take appropriate actions[11]. It is a function of the threat weapon carrying platforms, threat operational tactics, threat sensor characteristics, time, U.S. Navy force protection or escorts, JCC(X) signatures, and JCC(X) operational tactics. The metric or MoP (Ps) is the probability that the threat will detect, track, classify, continue to maintain track on the ship of interest, and close to a firing position. The concept of track maintenance is critical[16]. Figure 4 represents a notional output. As expected, the trend is that as we add capabilities and features the probability that the threat successfully develops situational awareness on our forces or ship is reduced.

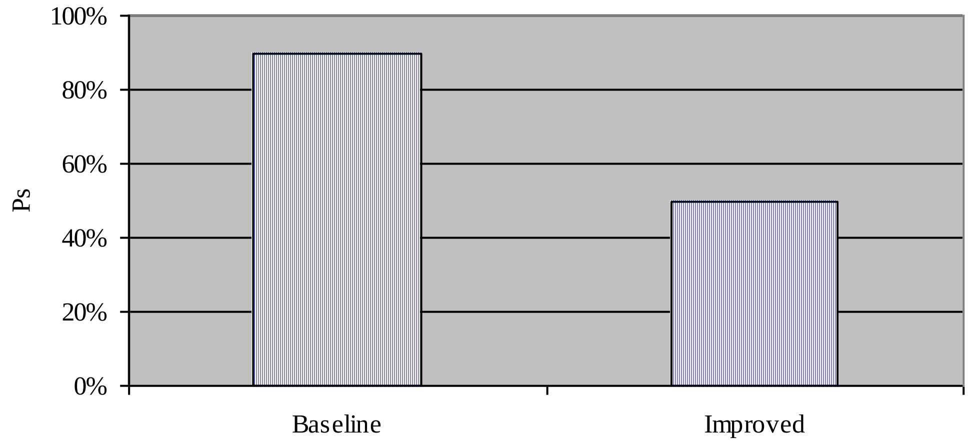

Figure 4. Notional Measure of Performance for Situational Awareness Assessment.

RESULTS: Engagement Assessment

The Engagement Assessment assumes that there is successful situational awareness by the threat to the point of sending out a strike package or launching threat weapons. This element is a function of ship organic self defense, force protection, threat platforms and weapons capabilities, and tactics. Figure 5 is a notional representation of the MoP (Pih/s) for the Engagement Assessment which is the probability of i hits given an attack. As we add capability, the overall probability of taking a hit is reduced and also the expected number of hits is reduced meaning the level of damage will be reduced.

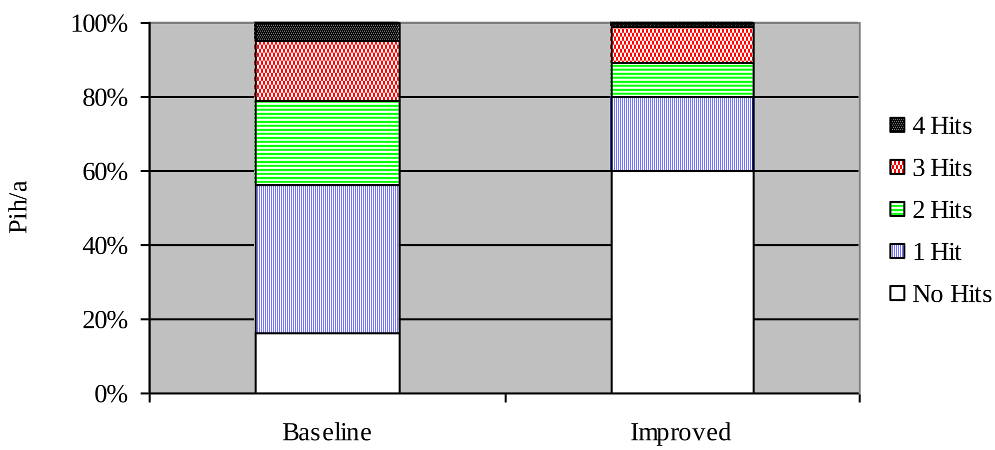

Figure 5. Notional Measure of Performance for Engagement Assessment.

RESULTS: Vulnerability Assessment

The Vulnerability Assessment assumes that one or more hits have occurred or an accident has happened and measures the effect on ship structure, stability, mission systems, and vital compartments.

Two primary metrics are developed in a Vulnerability Assessment, the probability of ship loss (Psk/ih) and probability of mission loss

(Pmk/ih), both given i hits. The probability of mission loss includes both ship loss as well as the direct loss of mission capability. For this TSSA, mission loss included the primary mission area as well as mobility.

Figure 6 is a representative example showing the MoP (Psk/ih) which is the probability of ship kill given i hits. As we add hardening or separation and redundancy, the likelihood of ship or mission loss is reduced. For this analysis the probabilities for each number of hits is absolute and does not account for the earlier number of hits.

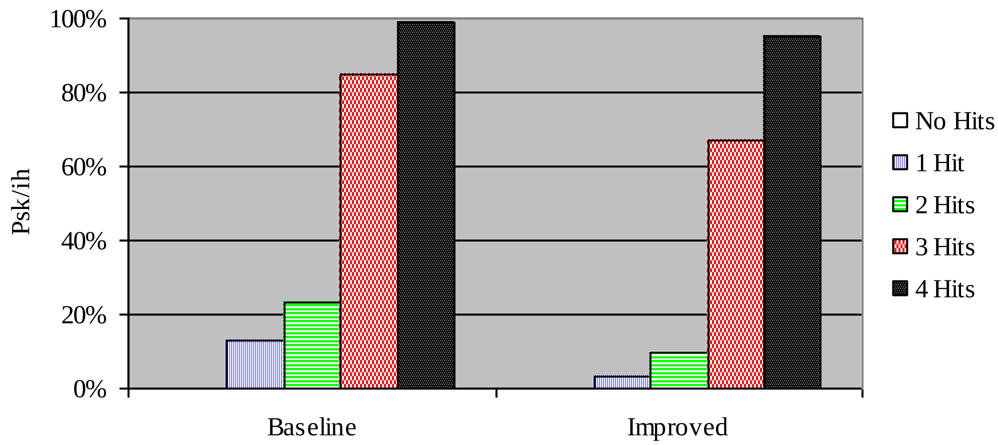

Figure 6. Notional Measure of Performance for Vulnerability Assessment.

RESULTS: Recoverability Assessment

The Recoverability Assessment assumes that one or more threat weapons have hit or an accident has occurred and the ship is not sunk due to primary damage. It measures the capability of the ship's crew to identify the primary damage and control and contain primary and secondary damage. The two metrics or MoPs are P(rs/ih) which is the probability of ship recovery given i hits and is shown in Figure 7 and P(rm/ih) which is the probability of mission recovery given i hits. In this case, ship recovery is used to indicate the ship's capability to withstand secondary damage such as fire, smoke, and progressive flooding. An additional element not considered here is the ability to restore power, dewater, eject smoke and restore mission capability.

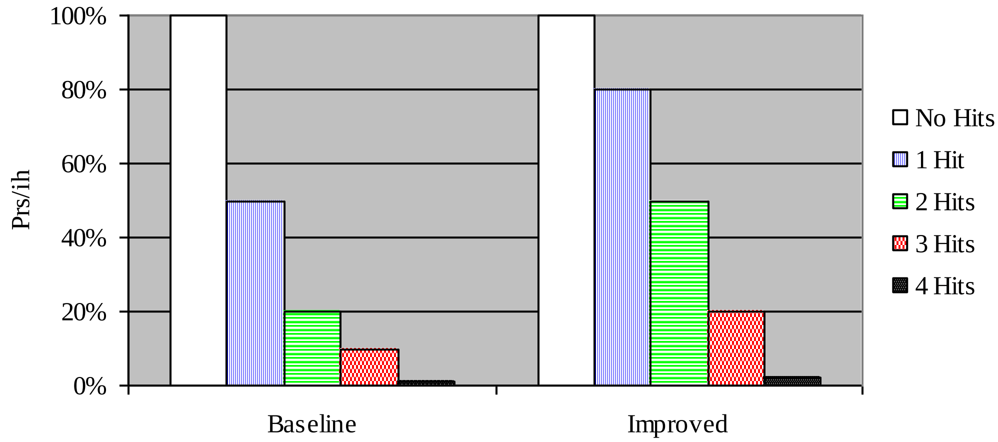

Figure 7. Notional Measure of Performance for Recoverability Assessment.

RESULTS: Integrating Assessment

Each of the previous four charts (Figures 4-7) captures a performance enhancement or MoP to the four functional elements of survivability. The question to the survivability decision-maker is which features are desired because they offer the most cost-effective improvements to the overall survivability of the ship. To determine this and to understand the impact at an operational level, the four elements need to be integrated.

The integration is done using Equations 1 and 2 and calculating the results for the pertinent information from the Situational Awareness, Engagement, Vulnerability, and Recoverability Assessments. A representative example is shown in Figure 8. It shows five notional concepts and captures the three potential outcomes (1: Ship survive and mission survive, 2: Ship survive and mission loss, and 3: Ship loss) for a particular threat in a particular operational situation. From the graph, Concept C appears to be the optimal because it is the one that minimizes ship loss through some combination of susceptibility reduction, vulnerability reduction, and recoverability enhancement. At this stage, the cost has not yet been factored nor has it been considered across all threats and operational situations.

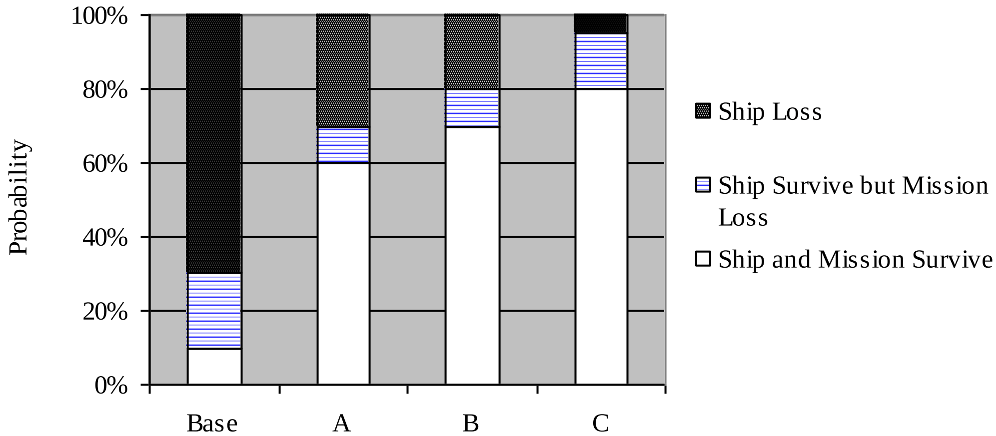

Figure 8. Notional Measures of Effectiveness for Survivability Integration Assessment.

RESULTS: Cost Assessment

A Cost Assessment was conducted concurrently with the Effectiveness Assessments. The Cost Assessment estimated the procurement and operation and support cost impacts for each feature or suite of features for the lead ship and three additional ships in class for the purposes of comparing cost and effectiveness impacts. The estimates were developed by NAVSEA 017, the Cost Engineering and Industrial Division. The procurement cost estimates were based on weight-based cost-estimating relationships with weight impacts and other non-material impacts provided by the appropriate technologists and integrated into a point design by the ship design tool.

RESULTS: Cost-Effectiveness

The cost-effectiveness of the various survivability features is captured by integrating the cost impact and effectiveness impact on a scatter plot, where an efficient frontier or Pareto optimal line can be shown. A notional example is shown in Figure 9. For a particular threat and operational situation, the impact on ship loss is shown as a function of procurement cost impact for approximately 75 survivability suites. These were developed from the individual list of features and impacts and combined where laws of independence were not violated and assumptions not invalidated. Each diamond represents one of 75 survivability suites added to the baseline concept which itself contained numerous low-cost, proven survivability features. The line connecting the upper-left most diamonds is called the efficient frontier. That is, for a given cost, no suite has a higher effectiveness or conversely, for a given effectiveness, no suite is less costly.

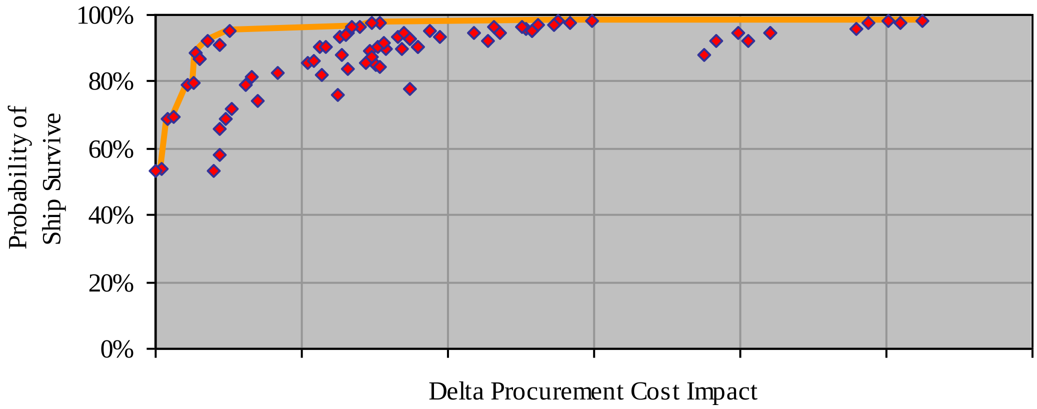

Figure 9. Notional Cost-Effectiveness Integrated MoEs Versus a Threat in an Operational Situation.

SUMMARY

Survivability requirements and their impact on life-cycle cost, the concept of operations, mission package, and ship size are key boundary conditions of any acquisition program and were recognized as such on the Joint Command and Control Ship (JCC(X)). To identify and understand the alternatives, a survivability systems engineering assessment was conducted using cost-effectiveness for comparison of various features including combat systems, signature reduction, countermeasures, hardening, separation and redundancy, damage control, and firefighting.

A successful TSSA or survivability systems engineering assessment requires several elements. A disciplined and structured approach is necessary for ensuring that effectiveness impacts are integrated to quantify cost-effectiveness across the spectrum of threat weapons, accidents, and operational situations. This implies a significant up-front investment in terms of time allocated for the assessment as well as resources to support it.

The challenge for survivability on the JCC(X) program in the near future is the closer integration of industry to the program in preparation of the release of the Request For Proposal. This closer cooperation will ensure the complete integration of the Fleet, acquisition community, and private industry which is ultimately required to truly understand and perform cost-effectiveness impact-based trades.

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BIOGRAPHIES

Norman R. Yarbrough is an employee of NAVSEA 05P3, the Ship Survivability Division. He graduated from the University of Maryland Baltimore County in 1988 with a Bachelor of Science degree in Mechanical Engineering, from the Catholic University of America in 1992 with a Master of Science in Engineering (Electrical), and from the Johns Hopkins University in 1994 with a Master of Science in Business (International Finance). He worked at NSWC Carderock as an Operations Research analyst in the areas of modeling and simulation, systems engineering, cost analysis for various technologies including signature reduction, combat systems, and vulnerability. He joined NAVSEA 05 in September of 1998 as a Total Ship Survivability Systems Engineer. He has supported numerous acquisition programs including the LPD 17, NSSN, CVN(X), and the JCC(X) programs as well as the Office of Naval Research leading cost-effectiveness assessments. He belongs to the American Society of Mechanical Engineers, the Military Operations Research Society, and the American Society of Naval Engineers.

Russell E. Kupferer is an employee of CSC Advanced Marine Center's Survivability Department. He graduated from Webb Institute in 1999 with a Bachelor of Science in Naval Architecture and Marine Engineering. He began working for CSC AMC (then Nichols Advanced Marine) in its engineering services department as a structural engineer in August of 1999. In May of 2000, he transferred to CSC AMC's Survivability Department. In his role as a survivability engineer, Russell has supported the Total Ship Survivability and Live Fire Testing and Evaluation programs for the CVN(X), DD21, JCC(X), LPD17, and T-AKE programs.