



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **SYSTEMS ENGINEERING CAPSTONE REPORT**

**ANALYSIS OF SHIPBOARD EFFECTS AND COVERAGE  
FOR THE INTEGRATION OF A HIGH-ENERGY LASER  
ON A LPD 17**

by

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June 2018

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## **ABSTRACT**

The project studied high-energy laser (HEL) integration into the Navy fleet using a systems engineering approach to identify the integration trade space with the objective of analyzing a systems engineering integration concept for the HEL applicable to LPD 17 class ships. Among the considerations for integrating a new weapon system, identification of a suitable location took priority. Minimum acceptable locations were based upon available Size, Weight, Power, and Cooling (SWAP-C) factors. Four single-HEL placement alternatives were identified which formed the basis for four additional alternatives created by combining fore and aft pairs. These eight alternatives were evaluated in comparison to one another to determine which provided the greatest overall capability and were least likely to suffer performance-degrading effects. From among the system requirements, five evaluation criteria were developed. These criteria used measures from scaled ship drawings to determine azimuthal and elevation coverage and the relative likelihood of effects from turbulence, environment, and shipboard operations. The concept study resulted in a recommendation for further studies and a more complete integration analysis.

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## TABLE OF CONTENTS

|      |                                               |    |
|------|-----------------------------------------------|----|
| I.   | INTRODUCTION.....                             | 1  |
| A.   | PROBLEM STATEMENT .....                       | 3  |
| B.   | BACKGROUND .....                              | 4  |
| 1.   | Current and Future HEL Systems .....          | 5  |
| 2.   | Integration Challenges and Concerns.....      | 6  |
| C.   | OBJECTIVES, ASSUMPTIONS, AND CONSTRAINTS..... | 11 |
| 1.   | Project Objectives .....                      | 11 |
| 2.   | Assumptions.....                              | 11 |
| 3.   | Constraints.....                              | 12 |
| D.   | SYSTEMS ENGINEERING PROCESS.....              | 13 |
| 1.   | Research and Requirements .....               | 14 |
| 2.   | Integration Concept Development.....          | 15 |
| 3.   | Concept Analysis and Delivery .....           | 17 |
| E.   | SUMMARY .....                                 | 18 |
| II.  | RESEARCH AND REQUIREMENTS.....                | 19 |
| A.   | STAKEHOLDER ANALYSIS .....                    | 21 |
| 1.   | Stakeholders .....                            | 22 |
| 2.   | Stakeholder Needs.....                        | 22 |
| 3.   | Stakeholder Analysis .....                    | 23 |
| B.   | REQUIREMENTS.....                             | 25 |
| III. | INTEGRATION CONCEPT DEVELOPMENT.....          | 31 |
| A.   | FUNCTIONAL ANALYSIS .....                     | 31 |
| 1.   | Functional Decomposition.....                 | 32 |
| 2.   | Physical Decomposition .....                  | 34 |
| B.   | DEVELOP CONCEPT ARCHITECTURE.....             | 36 |
| 1.   | Alternative A .....                           | 41 |
| 2.   | Alternative B.....                            | 43 |
| 3.   | Alternative C .....                           | 45 |
| 4.   | Alternative D .....                           | 47 |
| 5.   | Alternative AC .....                          | 49 |
| 6.   | Alternative AD .....                          | 50 |
| 7.   | Alternative BC.....                           | 51 |
| 8.   | Alternative BD.....                           | 52 |
| C.   | INTEGRATION CONCEPT .....                     | 54 |
| D.   | SUMMARY .....                                 | 59 |

|            |                                                                             |           |
|------------|-----------------------------------------------------------------------------|-----------|
| <b>IV.</b> | <b>CONCEPT ANALYSIS AND DELIVERY .....</b>                                  | <b>61</b> |
| <b>A.</b>  | <b>ANALYZE INTEGRATION CONCEPT .....</b>                                    | <b>61</b> |
| 1.         | Shipboard Operations Criterion (C09).....                                   | 62        |
| 2.         | Turbulence Criterion (C10) .....                                            | 68        |
| 3.         | Environment Criterion (C11) .....                                           | 72        |
| 4.         | Azimuthal Coverage Criterion (C21).....                                     | 74        |
| 5.         | Elevation Coverage Criterion (C22).....                                     | 76        |
| <b>B.</b>  | <b>DOCUMENT AND DELIVER.....</b>                                            | <b>78</b> |
| 1.         | Alternative A .....                                                         | 80        |
| 2.         | Alternative B.....                                                          | 81        |
| 3.         | Alternative C .....                                                         | 81        |
| 4.         | Alternative D .....                                                         | 82        |
| 5.         | Alternative AC .....                                                        | 83        |
| 6.         | Alternative AD .....                                                        | 84        |
| 7.         | Alternative BC.....                                                         | 85        |
| 8.         | Alternative BD.....                                                         | 85        |
| <b>C.</b>  | <b>SUMMARY .....</b>                                                        | <b>88</b> |
| <b>V.</b>  | <b>RECOMMENDATION AND AREAS FOR FURTHER STUDY .....</b>                     | <b>89</b> |
| <b>A.</b>  | <b>PROJECT OBJECTIVE QUESTIONS .....</b>                                    | <b>89</b> |
| 1.         | What Are the HEL Placement Possibilities on the LPD 17?<br>.....            | 89        |
| 2.         | What Are the HEL Placement Priorities? .....                                | 90        |
| 3.         | Is There an Advantage to Integrating Multiple HELs onto<br>an LPD 17? ..... | 91        |
| 4.         | What Are the Integration Challenges Involved? .....                         | 92        |
| 5.         | What Is the Most Ideal Integration Alternative?.....                        | 92        |
| <b>B.</b>  | <b>RECOMMENDATION.....</b>                                                  | <b>93</b> |
| <b>C.</b>  | <b>AREAS FOR FURTHER STUDY .....</b>                                        | <b>94</b> |
| 1.         | Hazard Identification and Risk Assessment.....                              | 94        |
| 2.         | Performance vs. Threat .....                                                | 94        |
| 3.         | Physical Measurements .....                                                 | 95        |
| 4.         | Impact of Shipboard Operations.....                                         | 95        |
| 5.         | Shipboard Turbulence Studies .....                                          | 96        |
| 6.         | Shipboard Environment Studies .....                                         | 97        |
| 7.         | Weapons Coverage and Blockage Mapping .....                                 | 97        |
| <b>D.</b>  | <b>SUMMARY .....</b>                                                        | <b>98</b> |
|            | <b>APPENDIX A. HISTORY OF HEL SYSTEMS .....</b>                             | <b>99</b> |

|                                              |            |
|----------------------------------------------|------------|
| <b>APPENDIX B. EVALUATION CRITERIA .....</b> | <b>107</b> |
| <b>LIST OF REFERENCES.....</b>               | <b>113</b> |
| <b>INITIAL DISTRIBUTION LIST .....</b>       | <b>117</b> |

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## LIST OF FIGURES

|            |                                                                                         |    |
|------------|-----------------------------------------------------------------------------------------|----|
| Figure 1.  | OV-1 High-level Overview of HEL Integration upon an LPD 17 Class Ship.....              | 2  |
| Figure 2.  | Artists’ Rendering Associated with Award of HELIOS Contract. Source: Keller (2018)..... | 5  |
| Figure 3.  | Integration Concept Venn Diagram .....                                                  | 7  |
| Figure 4.  | Systems Engineering Process .....                                                       | 14 |
| Figure 5.  | Systems Engineering Process (research and requirements phase).....                      | 19 |
| Figure 6.  | HEL context diagram.....                                                                | 20 |
| Figure 7.  | Integration Concept Development Phase.....                                              | 31 |
| Figure 11. | HEL Combination Alternatives—Azimuth Coverage .....                                     | 40 |
| Figure 12. | HEL Combination Alternatives—Elevation Coverage.....                                    | 40 |
| Figure 13. | HEL Alternative A—Azimuth Coverage.....                                                 | 42 |
| Figure 14. | HEL Alternative A—Elevation Coverage .....                                              | 43 |
| Figure 15. | HEL Alternative B—Azimuth Coverage.....                                                 | 44 |
| Figure 16. | HEL Alternative B—Elevation Coverage .....                                              | 45 |
| Figure 17. | HEL Alternative C—Azimuth Coverage.....                                                 | 46 |
| Figure 18. | HEL Alternative C—Elevation Coverage .....                                              | 47 |
| Figure 19. | HEL Alternative D—Azimuth Coverage.....                                                 | 48 |
| Figure 20. | HEL Alternative D—Elevation Coverage .....                                              | 49 |
| Figure 21. | HEL Alternative AC—Azimuth Coverage .....                                               | 50 |
| Figure 22. | HEL Alternative AC—Elevation Coverage.....                                              | 50 |
| Figure 23. | Alternative AD—Azimuth Coverage .....                                                   | 51 |
| Figure 24. | Alternative AD—Elevation Coverage .....                                                 | 51 |
| Figure 25. | Alternative BC—Azimuth Coverage .....                                                   | 52 |

|            |                                                                           |    |
|------------|---------------------------------------------------------------------------|----|
| Figure 26. | Alternative BC—Elevation Coverage.....                                    | 52 |
| Figure 27. | Alternative BD—Azimuth Coverage.....                                      | 53 |
| Figure 28. | Alternative BD—Elevation Coverage .....                                   | 53 |
| Figure 29. | Concept Analysis and Delivery Phase .....                                 | 61 |
| Figure 30. | Top-down View—Measured Distance to Nearest 30 mm Gun.....                 | 63 |
| Figure 31. | Top-down View Alternatives A and B Distance to Nearest 30 mm Gun.....     | 63 |
| Figure 32. | Alternative C Measurement to Nearest 30 mm Gun.....                       | 64 |
| Figure 33. | Top-down View—Measured Distance to Nearest RAM Launcher .....             | 65 |
| Figure 34. | Top-down View Alternatives A and B Distance to Nearest RAM Launcher ..... | 66 |
| Figure 35. | Top-down View Alternatives C and D Distance to Nearest RAM Launcher ..... | 66 |
| Figure 36. | Alternatives A-D Maximum Distance to Deck Edge .....                      | 68 |
| Figure 37. | Alternative A Maximum Distance to Deck Edge 25.5 Meters .....             | 69 |
| Figure 38. | Alternative B Maximum Distance to Deck Edge 42 Meters .....               | 70 |
| Figure 39. | Alternative C Maximum Distance to Deck Edge 72.5 Meters .....             | 70 |
| Figure 40. | Alternative D Maximum Distance to Deck Edge 71 Meters .....               | 71 |
| Figure 41. | Alternatives A-D Minimum Distance to Exhaust Stacks .....                 | 72 |
| Figure 42. | Alternatives A and B Minimum Distance to Forward Exhaust Stacks.....      | 73 |
| Figure 43. | Alternatives C and D Minimum Distance to aft Exhaust Stacks .....         | 73 |
| Figure 44. | Alternative BD Coverage Envelope.....                                     | 76 |

## LIST OF TABLES

|           |                                                                                                                                                |    |
|-----------|------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 1.  | Conclusion from HII Study of SSL-TM's Integration Impact to below Deck Equipment on the LPD 23. Source: (Flatley and LCDR Pilkerton 2017)..... | 25 |
| Table 2.  | Integration Requirements.....                                                                                                                  | 27 |
| Table 3.  | List of HEL Alternatives with Placement Descriptors .....                                                                                      | 38 |
| Table 4.  | HEL Alternatives Evaluation Criteria.....                                                                                                      | 55 |
| Table 5.  | HEL Evaluation Matrix <i>with examples</i> .....                                                                                               | 57 |
| Table 6.  | Weighted Pugh Matrix <i>with examples</i> .....                                                                                                | 58 |
| Table 7.  | Shipboard Operations (30 mm gun firing).....                                                                                                   | 65 |
| Table 8.  | Shipboard Operations (distance to nearest RAM launcher) .....                                                                                  | 67 |
| Table 9.  | Shipboard Operations (combined sum with Pugh score).....                                                                                       | 68 |
| Table 10. | Turbulence (maximum distance over deck).....                                                                                                   | 71 |
| Table 11. | Environment Criterion (distance to nearest exhaust stacks).....                                                                                | 74 |
| Table 12. | Azimuthal Coverage Criterion.....                                                                                                              | 75 |
| Table 13. | Elevation Coverage Criterion .....                                                                                                             | 77 |
| Table 14. | Summary Criterion Measures .....                                                                                                               | 78 |
| Table 15. | Unweighted Pugh Score Summary Table .....                                                                                                      | 79 |
| Table 16. | Pugh Matrix .....                                                                                                                              | 79 |
| Table 17. | Sampling of Other Factors .....                                                                                                                | 87 |

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## LIST OF ACRONYMS AND ABBREVIATIONS

|         |                                                      |
|---------|------------------------------------------------------|
| ABL     | airborne laser                                       |
| A/C     | air conditioning                                     |
| AFRL    | Air Force Research Laboratory                        |
| ALL     | Airborne Laser Laboratory                            |
| AOR     | area of responsibility                               |
| ARG     | amphibious ready group                               |
| ASCM    | anti-ship cruise missile                             |
| ATHENA  | advanced test high-energy asset                      |
| BDA     | battle damage assessment                             |
| BFTT    | battle force tactical training                       |
| CAD     | computer-aided design and drafting                   |
| CIC     | combat information center                            |
| CSISE   | combat system integrated support equipment           |
| DARPA   | Defense Advanced Research Projects Agency            |
| DDG     | guided missile destroyer                             |
| DLWS    | demonstration laser weapon system                    |
| DoD     | Department of Defense                                |
| ESG     | Expeditionary Strike Group                           |
| ESM     | energy storage module                                |
| FAC     | fast attack craft                                    |
| FIAC    | fast inshore attack craft                            |
| GA-ASI  | General Atomics-Aeronautical Systems, Inc.           |
| HEL     | high-energy laser                                    |
| HEL-MD  | high-energy laser – mobile demonstrator              |
| HELMTT  | high-energy laser mobile test truck                  |
| HELIOS  | high-energy laser with an integrated optical dazzler |
| HELLADS | high-energy liquid laser area defense system         |
| HM&E    | hull, mechanical and electrical                      |
| HPASS   | hybrid predictive avoidance safety system            |
| ICD     | interface control document                           |
| ISR     | intelligence, surveillance, and reconnaissance       |
| kW      | kilowatt                                             |
| LaWS    | laser weapons system                                 |

|        |                                                      |
|--------|------------------------------------------------------|
| LPD    | landing platform/dock                                |
| LWC    | laser weapons console                                |
| m      | meter                                                |
| mm     | millimeter                                           |
| MIRACL | mid-infrared advanced chemical laser                 |
| NPS    | Naval Postgraduate School                            |
| OV-1   | Operational Viewpoint - 1                            |
| PCM    | passive control measures                             |
| PCMS   | passive countermeasure system                        |
| Pk     | probability of kill                                  |
| POC    | Point of Contact                                     |
| PPE    | personnel protective equipment                       |
| PDRR   | program definition and risk reduction                |
| RADHAZ | radiation hazard                                     |
| RAM    | rolling airframe missile                             |
| RCS    | radar cross section                                  |
| RELI   | robust electric laser initiative                     |
| RPED   | rapid prototyping, experimentation and demonstration |
| rpm    | revolutions per minute                               |
| SE     | systems engineering                                  |
| SER    | stimulated emission of radiation                     |
| SBLRD  | space based laser readiness demonstration            |
| SNLWS  | surface navy laser weapons system                    |
| SSDG   | ship's service diesel generator                      |
| SSDS   | ship's self-defense system                           |
| SSL    | solid state laser                                    |
| SSL-TM | solid state laser – technology maturation            |
| SWAP-C | size, weight, power, and cooling                     |
| TAO    | tactical action officer                              |
| THEL   | tactical high-energy laser                           |
| TLCM   | tactical laser core module                           |
| TSM    | thermal storage module                               |
| UAS    | unmanned aircraft system                             |
| VLS    | vertical launch system                               |

## EXECUTIVE SUMMARY

The United States Navy is interested in integrating HEL weapon systems onto ships. HELs have the potential for increased capabilities against several current threats. The primary stakeholder expressed the utility of an HEL integrated onto an LPD 17 class ship that presents a feasible option toward satisfying an urgent operational need. The operational viewpoint (OV-1), Figure EX-1, illustrates an unescorted LPD 17 class ship stationed off the coast of Syria versus three types of threats that the HEL is required to combat: unmanned aircraft systems (UAS), fast attack craft (FAC) or fast in-shore attack craft (FIAC), and sub-sonic anti-ship cruise missiles (ASCM).



Figure EX-1. OV-1 High-level Overview of HEL Integration upon an LPD 17 Class Ship

Integration of a HEL upon an LPD 17 class ship poses unique challenges. Failure to meet the HEL weapons system's needs can introduce limitations and degrade its performance. Likewise, integrations such as this can result in the introduction of performance limitations to the LPD 17 class ship that would be equally unacceptable. Addressing these challenges in terms of size, weight, power, and cooling (SWAP-C) and

topside integration considerations, balanced against system performance, is the reason for undertaking this integration concept study.

A purpose-built SE process guided the conduct of this project. Figure EX-2 depicts eight steps focused on developing and analyzing the integration concept.

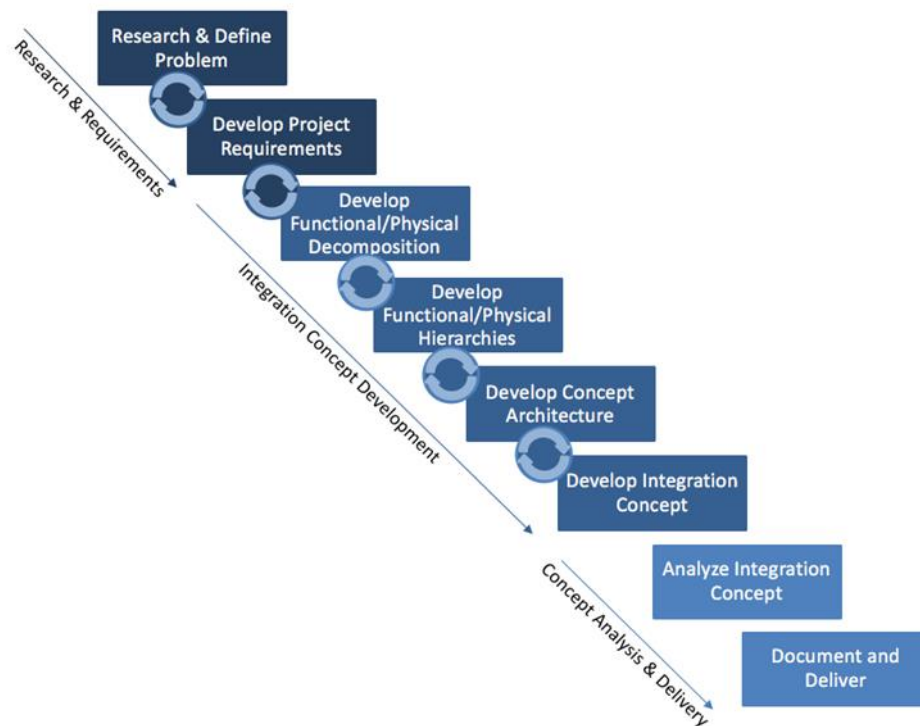


Figure EX-2. Systems Engineering Process

The research and define problem step began with the identification of stakeholders and resulted in a refined statement of their needs. After iterating project objectives with stakeholder feedback, the statement of needs formed the basis for requirements development. Following the definition of the requirements for the project, the next phase incorporated the four central steps of the process: develop functional/physical decomposition, develop functional/physical hierarchies, develop concept architecture, and develop integration concept. The final phase includes the steps: analyze integration concept and document and deliver. The first step in this phase applies the integration concept developed in the previous phase and analyzes its effectiveness in meeting the system

requirements. The second step is drafting a formal report that includes an explanation of the process, results of the analysis, and recommendations. It concludes with the delivery of the report. Concept analysis and delivery are connected in series with the preceding two phases, with no iterative or feedback relationship.

Development of the functional and physical decompositions is similar other than one focuses upon the system functionality and the other on the physical features. They both require identification and expression of these key items from the top-down. Each function and physical feature is deconstructed into its subsequent lower level functions and features. This continues until the purpose is met, or there are no more functions or features. This results in a functional decomposition and a physical decomposition each.

Development of the functional and physical hierarchies follows suit from the completed decompositions and moving from the top-down, beginning with the uppermost function and feature, connects each with the next lower level function(s) and feature(s). Each function or feature may have multiple lower-level children, but only a single higher-level parent. This is complete when all previously decomposed functions and features have been placed within the specific hierarchy in development.

The concept architecture helped with discovery and enabled thoughts such as:

Before one can identify locations and begin to consider whether space is available, it is critical to know how the components fit together.

Identifying placement possibilities first is important when integrating with an existing ship design.

The introduction of a new system within an existing footprint may require modifications to uphold structural integrity.

A new system may require tradeoffs with current weapons systems and their associated capabilities.

The integration concept used SWAP-C factors and fit of the HEL as the priority, which led to visualizing HEL placement alternatives and using scaled ship drawings as the

basis for analysis. Figure EX-3 shows one example with azimuth coverage indicated for all HEL alternatives.

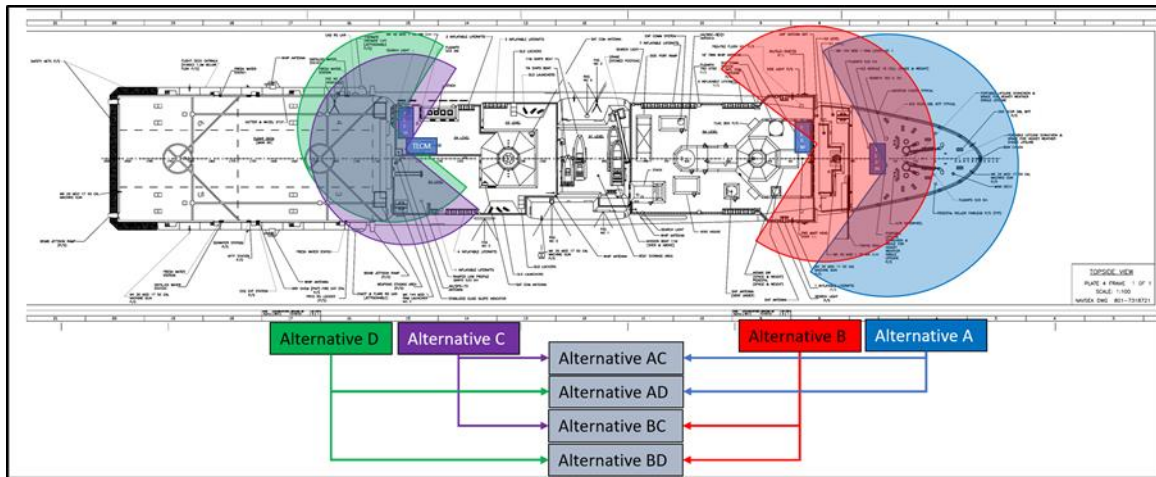


Figure EX-3. HEL Alternatives – Azimuth Coverage

Detailed descriptions for the alternative locations on the LPD 17 are as follows: Alternative A is located on the bow centerline in a position identified for a VLS. Alternative B is located above the bridge on the port side. Alternative C is located aft of amidships on the centerline. Alternative D is aft of the ship's exhaust stacks on the port side. Alternative AC has two HELs, one on the bow centerline in a position identified for a VLS and the second is aft of amidships on the centerline. Alternative AD has two HELs, one on the bow centerline in a position identified for a VLS and the second is aft of the ship's exhaust stacks on the port side. Alternative BC has two HELs, one is located above the bridge on the port side and the second is located aft of amidships on the centerline. Alternative BD has two HELs, one is located above the bridge on the port side and the second is aft of the ship's exhaust stacks on the port side. The alternatives are listed in Table EX-1 along with placement descriptors to help visualize their relative position on the LPD.

Table EX-1. List of HEL Alternatives with Placement Descriptors

| <b>Alternatives</b> | <b>Placement Descriptors</b> |
|---------------------|------------------------------|
| A                   | Bow-Low                      |
| B                   | Bridge-High                  |
| C                   | Aft-Centerline               |
| D                   | Aft-Port                     |
| AC                  | Bow-Low, Aft-Centerline      |
| AD                  | Bow-Low, Aft-Port            |
| BC                  | Bridge-High, Aft-Centerline  |
| BD                  | Bridge-High, Aft-Port        |

The drawings also led to the development of an approach for evaluation of alternatives in support of the integration concept analysis. Evaluation criteria were developed for each system requirement. Other drawings provide closer views and served to provide indicators useful for some of the criteria. This realization resulted in down selection to a subset of five evaluation criteria for use in the analysis. Table EX-2 lists the evaluation criteria used in the analysis.

Table EX-2. HEL Alternatives Evaluation Criteria

| Number | Criteria                                   | Evaluation method                         |
|--------|--------------------------------------------|-------------------------------------------|
| C09    | Effects of shipboard operations (minimize) | Distance between TLCM and ship's systems  |
| C10    | Turbulence (minimize)                      | Distance laser beam must travel over deck |
| C11    | Environment effects (minimize)             | Distance between TLCM and exhaust stacks  |
| C21    | Coverage - azimuth (maximize)              | Degree range                              |
| C22    | Coverage - elevation (maximize)            | Degree range                              |

Once the criteria were established, the analyze integration concept phase called for obtaining measures to populate the supporting Pugh matrix tables for evaluation of each of the five criteria. The measures were obtained through use of scaled ship drawings for each of the eight alternatives. The raw values for the criterion measures are summarized in Table EX-3.

Table EX-3. Summary Criterion Measures

|      | Shipboard Operations             |                                      | Turbulence                 | Environment                            | Azimuthal coverage | Elevation coverage |
|------|----------------------------------|--------------------------------------|----------------------------|----------------------------------------|--------------------|--------------------|
|      | Distance to nearest 30mm Gun (m) | Distance to nearest RAM launcher (m) | Max distance over deck (m) | Distance to nearest exhaust stacks (m) | Coverage sector(s) | Coverage sector(s) |
| Alt. | Maximize                         | Maximize                             | Minimize                   | Maximize                               | Maximize           | Maximize           |
| A    | 10.0                             | 14                                   | 25.5                       | 57                                     | 230°               | 146°               |
| B    | 10.5                             | 8.8                                  | 42                         | 40                                     | 245°               | 157°               |
| C    | 8.5                              | 14.9                                 | 72.5                       | 9.2                                    | 250°               | 151°               |
| D    | N/A                              | 21.5                                 | 71                         | 5.2                                    | 270°               | 156°               |
| AC   | 10.0, 8.5<br>(Avg. 9.25)         | 14, 14.9<br>(Avg. 14.45)             | 25.5, 71<br>(Avg. 48.25)   | 57, 9.2<br>(Avg. 33.1)                 | 230°, 250°         | 146°, 151°         |
| AD   | 10.0, N/A<br>(Avg. 10)           | 14, 21.5<br>(Avg. 17.75)             | 25.5, 72.5<br>(Avg. 49)    | 57, 5.2<br>(Avg. 31.1)                 | 230°, 270°         | 146°, 156°         |
| BC   | 10.5, 8.5<br>(Avg. 9.5)          | 8.8, 14.9<br>(Avg. 11.85)            | 42, 71<br>(Avg. 56.5)      | 40, 9.2<br>(Avg. 24.6)                 | 245°, 250°         | 157°, 151°         |
| BD   | 10.5, N/A<br>(Avg. 10.5)         | 8.8, 21.5<br>(Avg. 15.15)            | 42, 72.5<br>(Avg. 57.25)   | 40, 5.2<br>(Avg. 22.6)                 | 245°, 270°         | 157°, 156°         |

The analysis leveraged the scaled ship drawings, data (measurements) pulled from the drawings, and the evaluation criteria through a modified Pugh matrix method to compare the alternatives to determine which should be the preferred alternative. Each alternative was ranked in accordance with minimizing and maximizing the data as required. Next, the Pugh score of 1, 0, or -1 needed to be applied. To do this, a normal distribution was utilized, and ranks 1–2 received the 1 score, ranks 3–6 received the 0 score, and ranks 7–8 received the -1 score. The unweighted, normally distributed Pugh scores are summarized for all criteria in Table EX-4.

Table EX-4. Unweighted Pugh Score Summary Table

|    | Shipboard<br>operations<br>C09 | Turbulence<br>C10 | Environment<br>C11 | Azimuthal<br>coverage<br>C21 | Elevation<br>coverage<br>C22 |
|----|--------------------------------|-------------------|--------------------|------------------------------|------------------------------|
| A  | 0                              | 1                 | 1                  | -1                           | -1                           |
| B  | 0                              | 1                 | 1                  | -1                           | 0                            |
| C  | -1                             | -1                | -1                 | 0                            | -1                           |
| D  | 1                              | -1                | -1                 | 0                            | 0                            |
| AC | 0                              | 0                 | 0                  | 0                            | 0                            |
| AD | 0                              | 0                 | 0                  | 1                            | 0                            |
| BC | -1                             | 0                 | 0                  | 0                            | 1                            |
| BD | 1                              | 0                 | 0                  | 1                            | 1                            |

The results in Table EX-5 show that the dual HEL mount, alternative BD, received the highest value after weights were applied and without further interpretation would imply that it best satisfied the requirements according to the evaluation criteria.

Table EX-5. Pugh Matrix

|        | Shipboard<br>operations<br>C09 | Turbulence<br>C10 | Environment<br>C11 | Azimuthal<br>coverage<br>C21 | Elevation<br>coverage<br>C22 | Totals |
|--------|--------------------------------|-------------------|--------------------|------------------------------|------------------------------|--------|
| Weight | 0.15                           | 0.20              | 0.15               | 0.25                         | 0.25                         | 1.0    |
| A      | 0                              | 0.20              | 0.15               | -0.25                        | -0.25                        | -0.15  |
| B      | 0                              | 0.20              | 0.15               | -0.25                        | 0                            | 0.10   |
| C      | -0.15                          | -0.20             | -0.15              | 0                            | -0.25                        | -0.75  |
| D      | 0.15                           | -0.20             | -0.15              | 0                            | 0                            | -0.20  |
| AC     | 0                              | 0                 | 0                  | 0                            | 0                            | 0      |
| AD     | 0                              | 0                 | 0                  | 0.25                         | 0                            | 0.25   |
| BC     | -0.15                          | 0                 | 0                  | 0                            | 0.25                         | 0.10   |
| BD     | 0.15                           | 0                 | 0                  | 0.25                         | 0.25                         | 0.65   |

There was sufficient influence from other factors that required interpretation before recommending an alternative for this integration. It was necessary to break out each alternative separately, and to consider factors other than the Pugh matrix results. Other

factors included what was known, good and bad. Considering these factors about each alternative enabled a comprehensive and clear understanding of possible achievements.

Given the analytical (Pugh matrix) results and further interpretation of each alternative, it was clear that pronouncing a distinct alternative as the recommended best option would be premature. Ideally, the scope of this analysis would allow for selecting a “best” alternative based on the admittedly limited evaluation criteria. Strictly based on the outcome of the Pugh matrix method, alternative BD would be the only choice; however, this is not the case. The Pugh matrix results do not automatically equate to a final recommendation because there are factors that still need consideration. Table EX-6 includes a sampling of other factors that were not covered by the evaluation criteria analyzed using the Pugh matrix method. This sampling of factors points to impacts of and on the alternatives that one should consider before selecting any single alternative as the best.

Table EX-6. Sampling of Other Factors

| <b>Sampling of Other Factors</b>                                                                                                                                                                                                                                                                                                                                                                                                           | <b>Alternative(s) Affected</b> |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|
| Protection from weather and combat damage; reduced impact from corrosive sea environment                                                                                                                                                                                                                                                                                                                                                   | Alternative A                  |
| Reduced impact on ship's RCS relative to other alternatives                                                                                                                                                                                                                                                                                                                                                                                | Alternative A                  |
| Potential re-use of cabling, wiring, framing when replacing 30 mm gun                                                                                                                                                                                                                                                                                                                                                                      | Alternative D                  |
| Increased impact from crashing waves; more frequent, near-continuous sea spray                                                                                                                                                                                                                                                                                                                                                             | Alternative A                  |
| Risk of personnel hazards from operation of HEL                                                                                                                                                                                                                                                                                                                                                                                            | All                            |
| Increase to ship's RCS; additional cost from addition of PCMS to components                                                                                                                                                                                                                                                                                                                                                                | All                            |
| Risk related to weight distribution from containers on decks not designed for the weight                                                                                                                                                                                                                                                                                                                                                   | All                            |
| Challenge adding additional wiring and cabling to support HEL components above bridge                                                                                                                                                                                                                                                                                                                                                      | Alternative B                  |
| Potential additional complexity and cost to re-design 30 mm gun placement to support HEL                                                                                                                                                                                                                                                                                                                                                   | Alternative D                  |
| Coordination of operations and safety before, during, and after flight operations                                                                                                                                                                                                                                                                                                                                                          | Alternatives C and D           |
| Coordination/de-confliction of operations between HEL and other ship's weapons (i.e., 30 mm gun barrel being hit by laser beam, HEL components within fall pattern of expended 30 mm shell casings; timing and tactical engagement decisions during simultaneous engagement on same target or multiple targets)                                                                                                                            | All                            |
| Potential lack of desired net capability gain by adding HEL but removing 30 mm gun                                                                                                                                                                                                                                                                                                                                                         | Alternative D                  |
| Pugh matrix method results do not include the cumulative effects of the evaluation criteria due to the application of weighting. An alternative may have excellent coverage but also be near to sources of turbulence, environment, and shipboard operation impacts such that it suffers the cumulative effects of all three, truly limiting the HEL performance even though it has the capability to nominally provide excellent coverage | All                            |

The primary recommendation of this case study was to review, refine, and repeat a similar SE process with new and revised evaluation criteria evolved from a more comprehensive set of system requirements. A secondary recommendation was to complete a sensitivity study ensuring the weighted values for each evaluation criteria clearly align with the intent of the study. Finally, in conjunction with these recommendations, it is highly encouraged that the following areas for further study receive full consideration for funding and resource support:

- Hazard identification and risk assessment
- Performance vs threat
- Physical measurements
- Impact of shipboard operations
- Shipboard turbulence studies
- Shipboard environment studies
- Weapons coverage and blockage mapping

Once these areas are adequately studied, the Navy should be well positioned to undertake the planning and execution of integrating a HEL weapon system onto an LPD 17 class ship. In fact, this case study in combination with the results of these studies should be more than suitable to inform the earliest stages of preparation for integration of a HEL weapon system on nearly any surface naval vessel with slight adjustments and tailoring.

## ACKNOWLEDGMENTS

It is with love and profound appreciation that we must thank our families. There can be no making up for time lost, no “do-overs” of life’s special moments, and no extra hugs or kisses for those missed. No form of thanks suffices for their having pretended our moods and attitudes were not at times painful to endure. They suffered while wanting both our success and our presence. They gave us unconditional love and support from day one and together we completed this life-altering achievement.

To our co-workers who took up the slack when our minds strayed to schoolwork without our even realizing, and to our friends who listened to our complaints or did without us at both the routine and special events—we can only say thank you!

Finally, to our advisors who guided our every step, pushed us to expand our minds, and reined in our over-exuberant ideas, we can only tell you how much we appreciate your commitment and the sacrifices made in our interest. You will always occupy a special place in our memory. Thank you very much!

—Adrien, Dale, Dean, Kelly, and Scott

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## I. INTRODUCTION

For decades, the Department of Defense (DoD) has researched the possibilities of incorporating high-energy laser (HEL) weapons systems onto operating platforms (Schroeder 2016). Lasers have gained greater attention in recent years because of the potential that this technology harnesses. The 2015 Congressional Research Service report, *Navy Shipboard Lasers for Surface, Air, and Missile Defense: Background and Issues for Congress* (O'Rourke 2015), highlights the importance of lasers to the Navy:

Lasers are of interest to the Navy and other observers as potential shipboard weapons because they have certain potential advantages for countering some types of surface, air, and ballistic missile targets. Shipboard lasers also have potential limitations for countering such targets. (O'Rourke 2015, 2)

Successfully developing, integrating, and deploying a HEL weapon system alongside current ship self-defense systems would revolutionize naval surface doctrine for years to come. HEL weapon systems have the potential to be more efficient against threats and more cost-effective as compared to conventional weapons systems. Not since the development of shipboard missiles has, a new technology offered such a potential advantage over its adversaries (O'Rourke 2015).

The U.S. Navy is interested in integrating HEL weapon systems onto ships. HELs have the potential for increased capabilities against several current threats. The HEL capability includes operating at reasonable ranges with significant cost savings versus the use of traditional weapons. Directed energy weapons cost “dollars per shot” rather than the thousands of dollars for a gun round or millions of dollars for an interceptor missile, such as the Standard Missile-2 (Coffey 2014).

To represent a system visually, the Department of Defense Architecture Framework (DoDAF) provides visualization models for communicating system infrastructure and their needs and requirements. Figure 1 is the high-level overview called an Operational View 1 (OV-1) representing a HEL integration upon an LPD 17 class ship.

The OV-1 identifies the high-level operational requirements from the stakeholder by showing the various functions or operations that the system must perform. The vignette,

as depicted, is of an unescorted LPD 17 class ship stationed off the coast of Syria performing operations. The stakeholder classifies three types of threats that the HEL is required to combat. The primary threat is against an unmanned aircraft system (UAS) in that the HEL will be required to perform counter-UAS and defend against single or small groups of UAS. The secondary threat is a group of small surface combatants, also referred to as fast attack craft (FAC) or fast in-shore attack craft (FIAC). The HEL must be able to defend the LPD 17 class ship against a small group of FAC/FIAC, typically seen near the littorals. The tertiary threat is a sub-sonic anti-ship cruise missile (ASCM). The HEL must be able to eliminate an inbound subsonic ASCM with parameters similar to the C-802 Styx, a subsonic cruise missile in use, according to Shay (2016), by terrorist groups in the Middle East (Shay 2016).

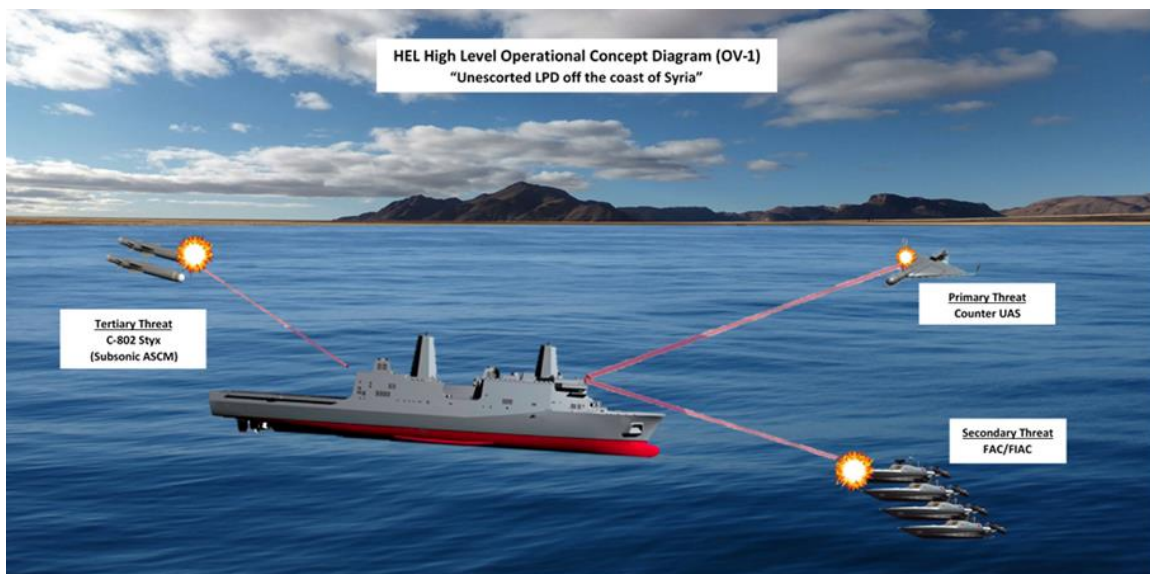


Figure 1. OV-1 High-level Overview of HEL Integration upon an LPD 17 Class Ship

As with the advent of missile systems and their subsequent integration onto ships, which began in the mid-1940s, significant challenges must be overcome if the Navy is to properly leverage the full promise of this new HEL capability. Since the time of missile systems integration, the problem of “fitting” a system onto a ship when it was not originally part of the ship’s design has arguably grown more complicated. Ships of today capitalize

on a myriad of systems; each integrated to form a larger overall system that is the ship itself. While designs initially include reserves in size, weight, power, and cooling (SWAP-C) as well as in bandwidth and frequency assignments across the electromagnetic spectrum, successful introduction of an entirely new weapon system is by no means a foregone conclusion. Failure to meet the new system's needs can introduce limitations and degrade its performance. Likewise, integrations such as this can result in performance limitations being introduced to the overall system, which would be unacceptable.

A balance between SWAP-C, topside integration, and system performance versus the threat of small boat swarms, unmanned aerial systems, and/or missiles must be achieved in harmony with the existing shipboard systems. The integration should consider the expansion of future HEL weapon systems, and/or other shipboard systems with regard to the reserves just mentioned. Application of a disciplined SE process will aid in effectively and properly considering these integration challenges while helping to achieve this balancing act. The first steps of this process are to define the problem.

#### **A. PROBLEM STATEMENT**

Throughout the history of warfare, there has been a race between development of offensive weapons and development of the means to defend against those weapons. The Navy faces a variety of current and evolving threats. In addition to aircraft, other ships and submarines, these threats include small boat swarms, unmanned aerial vehicles, unmanned surface and sub-surface vehicles, hypervelocity projectiles, anti-ship missiles, and ballistic missiles. Laser weapon systems present the potential answer to many of these threats. The Navy wants LPD 17 class ships to be capable of self-defense against small boat swarms, unmanned aerial vehicles, and subsonic anti-ship missiles. "Laser weapons exhibit a number of characteristics that offer important advantages...Foremost is the speed of light...[with] the limitations imposed by fly-out time of conventional weapons...virtually eliminated...unprecedented aimpoint selection...low collateral damage...deep magazines... [a low] marginal cost of additional engagements...[and] graduated effects on the target" (Perram 2010, 12–14). The Navy believes that a HEL may be the solution and this study aims to identify and analyze an integration concept to support that possibility.

The Navy plans to employ HEL weapon systems in the fleet to provide a continuous magazine at far greater affordability per shot to address adversarial threats that are exceeding the current capabilities of existing shipboard kinetic weapon systems and tactical options. Implementation of HEL systems in the fleet poses a significant integration challenge. HEL systems must be integrated onto ships to optimize intended performance against threats while operating within the capabilities and limitations inherent to the host platforms.

The project studied HEL integration into the Navy fleet using a systems approach to identify the integration trade space with the objective of analyzing a systems engineering integration concept for the HEL applicable to LPD 17 class ships. The project deliverable is a HEL integration concept study for LPD 17 Class Ships.

## **B. BACKGROUND**

Based on the nature of the U.S. Navy's mission and its operational theaters, naval platforms have shown a need for offensive and defensive weapon systems. The Navy highly desires new weapon systems or concepts they believe capable of filling offensive or defensive roles. The Navy investigates such systems and concepts for fleet-wide application and pursues integration when feasible.

The Navy conducted an afloat deployment and testing of a prototype HEL on the USS Ponce. Development of a HEL weapon system for use on board the DDG-51 class has begun in earnest, and plans for creating an integration testbed between Solid State Laser—Technology Maturation (SSL-TM) program and an LPD 17 class ship are underway. While each of these steps or actions align to a specific aim, in the end, decisions made concerning SWAP-C and topside integration will dictate the early success or failure of HEL weapon systems for the fleet. For further context, an abbreviated history of HEL systems has been included as Appendix A.

## 1. Current and Future HEL Systems

The Naval Sea System Command's Program Executive Office for Integrated Weapons Systems (PEO IWS) is developing the 60 kW High Energy Laser with Integrated Optical Dazzler (HELIOS).

- (2018) "U.S. Navy [awarded] a \$150 million contract...to the Lockheed Martin Laser and Sensor Systems...to develop a combination laser weapon and electro-optical dazzler to disable optical sensors called the HELIOS system." (Keller 2018) Figure 2 depicts HELIOS in action.



Figure 2. Artists' Rendering Associated with Award of HELIOS Contract.  
Source: Keller (2018).

The Office of Naval Research (ONR) and Northrop Grumman team is developing the Solid-State Laser Technology Maturation (SSL-TM) program to a near-term goal of 150 kW class HEL, while incorporating new technologies such as an off-axis beam director and spectral beam combining. Additionally, the Navy recognizes the potential scalability of laser weapons system technology. Scalability allows for increasing the power output while maintaining similar footprint, or miniaturizing the system while maintaining the pre-existing power output levels. Either way, opportunities abound for HEL integration on a variety of different platforms.

## **2. Integration Challenges and Concerns**

The challenge not being discussed is how best to approach the integration of this multi-component, complex system into a pre-existing, purpose-built larger and even more complex system. Each variant of a HEL, designated for installation upon a class of warship, has particular needs that require attention. Each HEL variant must achieve harmony with the other systems on the ship and the ship itself to support its mission set. These include, but are not limited to, the following: size, weight, power, and cooling (SWAP-C). However, that story is not one-sided; the ship also has SWAP-C factors that require attention.

Hypothetically, one could make the perfect match between HEL and ship SWAP-C factors, yet still result in failure. Integration is more than just the physical and electronic characteristics; it is less science and more art. It is where the systems engineer is essential. Figure 3 illustrates the integration concept as the three-way junction between the operational, technical, and functional realms. The three-dimensional solution can be elusive to identify and prohibitively expensive, in both cost and performance, to achieve if not done with appropriate care.

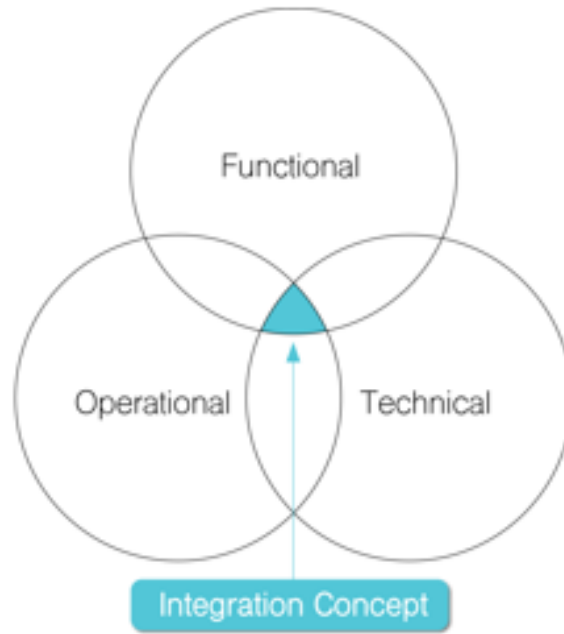


Figure 3. Integration Concept Venn Diagram

This integration required a systems engineering process. The team used the SE process to assess the HEL's component placement effectiveness within the available space constraints. The HEL's component placement was measured against the point where azimuth and elevation coverage are optimized.

The process also drives changes necessary to achieve validation of the system throughout the course of developmental and operational testing.

***a. Size and Weight versus Stability and Topside Design***

Naval surface platforms are constrained by various limitations. They must conform to the laws of nature. For any system (with physical features) placed aboard, the ship is subject to the effects of both the size and weight of the object. Obviously, a system's physical components occupy the space described by its measures in three dimensions (e.g., length, width, and depth). As an absolute minimum, available space on the platform must be greater than the component measures in each dimension in order for it to fit. Just because a location meets this constraint, does not mean the location is suitable, since there remain many additional factors to consider. For each component, one must ensure to consider the

allowance for interfaces and associated connections (wiring, piping, ducting, vibration isolators, enclosures, fasteners, and such). This includes specifications that dictate other constraints such as maximum allowable “run” length (distance between the two connected components, which can affect performance due to losses, for example) or maximum vertical height of piping.

Buoyancy is one of the principles that affects floating objects, and thus the weight of a system’s physical components is another prime consideration. Every hull form has a limit, so with the addition of weight, performance decreases in maneuverability and stability. Stability includes another factor, in that height above centerline and distance “outboard” (port or starboard) from centerline multiply the effect of additional weight. Ideally, the weight is added only at the centerline and as near the keel as possible; however, this is impractical. The addition of a weapon system to a platform, while not an absolute, nearly always requires component installation “topside” on or above the weather decks (on the exterior of the platform above the main deck and can include items high on the mast). One must carefully study such placement, taking every effort to minimize weight, identify the lowest possible and centerline-most locations while balancing the interface and connection limitations previously discussed. Size, weight, and positioning of a system’s components offer trade space opportunities during the design and integration phases. Trade space is “a set of operational and system parameters, attributes and characteristics to provide possible design options and satisfy operational expectations and system performance criteria” (Smead 2015). Trade space decisions made by the integrators will ultimately have an impact on the system’s performance.

#### ***b. Power and Cooling versus Energy Storage***

HEL system integration onto a naval surface platform requires that power, cooling, and energy storage be well understood. The combination of these three factors will determine the baseline performance capability of the HEL, given the size and weight limitations determined as previously discussed. The efficiency of solid-state lasers (SSL) used in the HEL systems under consideration in this report, has reached 10–30% (O'Rourke 2015) and continues to improve. More specifically, the “current cutting edge for fiber-optic

lasers is at 30–35%” according to Lockheed Martin Senior Fellow Rob Afzal (Freedberg Jr 2015). An efficiency of 25% means a laser with an output of 30 kW would need 120 kW of power to operate, thus the platform must have the ability to provide the laser with that amount of energy on demand. All naval surface platforms have a known amount of electrical power created, in-use, and available at any given time. The engineering and operational usage of electrical power as well as design features of the electrical distribution systems are specified to provide power in a manner, which best suits the ship. Without great forethought and study, no new system should be installed that will violate this critical balance.

In addition to the power requirements necessary to reach the desired output power of the laser, the considerable heat generated during firing must be dissipated safely. Although dictated by design, the platform must either provide electricity to the HEL to power its internal cooling system, or provide the source of cooling, most commonly via chilled water. The power requirement to support cooling depends on, the laser power output.

Even without the large electrical demand of a HEL, surface naval platforms must manage the limited power available. Electrical distribution for shipboard systems receives priority because they are critical to mission accomplishment. For example, air conditioning for cooling of weapons and communications system electronics takes priority over that of air conditioning for habitability or crew comfort. Unique HEL characteristics will further complicate the energy management challenge. In the case of an SSL, “the higher the output power, the greater the temperature in the medium and the more risk that damage to the medium will occur” (Valiani 2016). Since power output of a HEL has direct performance connotations, the Navy is necessarily striving for higher power output from these systems. Higher power HEL systems not only draw more power just to operate, but they will require more power from the cooling system because of the need to dissipate more heat.

For a higher power HEL, ~150 kW with an efficiency of 35%, the energy management concern for the electrical distribution priority of the weapon system, becomes a question of sufficient power available. Can the ship’s electrical generation capacity afford this additional load of ~430 kW? It is entirely likely that “this is more energy than a ship

can provide, so the use of an energy storage system is vital to the successful integration of HELs onto naval platforms” (Valiani 2016).

Also, according to Valiani

There are many different types of energy storage technologies including, but not limited to, batteries and flywheels...Lead acid batteries are a mature and safe technology already onboard Navy ships [and there is] a newer technology...lithium-ion batteries [to consider]. Lead acid batteries tend to take...hours to recharge and should not be discharged lower than 50 percent...[where] lithium-ion batteries...charge faster...[and a better discharge tolerance (~80 to 90 percent). A flywheel is a device that rotates at very high speeds (~60,000 rpm) that can convert this mechanical energy into electrical energy [9]...A drawback to flywheels is there are no commercial off the shelf solutions available, so the energy storage system would have to be specifically designed for the platform. (2016, 21-23)

Consideration of energy storage needs early in the development of an integration concept is necessary. Failure to do so could lead to less effectiveness and/or greater cost for the integration effort.

***c. Degree of Integration with the Combat System***

Integrating the HEL into a ship’s combat system presents three options. The first is complete integration; the second is partial integration, and the third is no integration. Working in reverse order, no integration leaves the HEL to perform as a stand-alone system dependent upon its own sensors and operator direction to conduct the detect-to-engage sequence. This option would result in the least effective capability in terms of the larger, overall system performance. The second option for partial integration has its own degree of variation from a specially wired connection for passively receiving data (passive one-way tap) to a degree shy of complete two-way integration. The choice is between cost and performance. The first option for full integration represents maximum achievable performance at the highest cost with the greatest integration risk. Among these options lies an optimum choice in terms of the overall integration, by trading off between performance capability, cost, and risk, depending upon resource availability.

## **C. OBJECTIVES, ASSUMPTIONS, AND CONSTRAINTS**

To bound the scope of this HEL integration, objectives, assumptions, and constraints are captured and tracked. A visual representation of the mission and operational scenario is called an OV-1, and is represented by Figure 1. The OV-1 was a useful tool in beginning to scope the program.

### **1. Project Objectives**

The overarching objective of this project was to identify and study the challenges of integrating HEL systems onto naval surface platforms. The study focused on the HEL integration onto LPD 17 platforms. The primary objective was to express a collective understanding of systems engineering concepts and practice. A secondary objective was to provide a useful document to the Navy for potential use in integrating HEL systems onto naval surface platforms. A tertiary objective was to provide a useful tool for other DoD platforms for potential use on non-naval platforms.

The integration of the HEL onto an LPD 17 primarily focused on two questions. “What are the placement possibilities?” and “What are the placement priorities?” These questions take into account many factors. The placement of the HEL’s components can affect the ship in many different ways from use of limited space, impacts on stability and the performance of other systems, to the changes in the ship’s radar cross-section and more. Obstructions could limit the HEL’s coverage due to the ship’s many topside features. Specifically, the team aimed to answer the following set of questions in support of meeting the project objectives:

1. What are the HEL placement possibilities on the LPD 17?
2. What are the HEL placement priorities?
3. Is there an advantage to integrating multiple HELs onto an LPD 17?
4. What are the integration challenges involved?
5. What is the most ideal integration alternative?

### **2. Assumptions**

The team developed the following set of study assumptions:

- HEL systems under consideration are operational or otherwise fielded.
- Some modifications to either HEL or LPD are anticipated in order to make the integration fit.
- Solution will not address “installation” beyond position/location details.
- Duration of continuous or pulsed shots and length of engagement are factors of design, thus will result from the combination of system features and available power.
- HEL may be acquired from commercial or industry sources.
- HEL integration shall be accomplished using an “Art of the possible” solution. Art of the possible is defined as Technology Readiness Level (TRL) level 6 or greater for the system and any components.
- HEL-LPD Integration Interface Control Document (ICD) exists and contains the data types needed for the requirements.
- HEL, as designed, already includes the ability to acquire, track, select an aimpoint, determine how long to fire, conduct BDA, and re-engage.

### **3. Constraints**

Constraints are those items that limit the project in terms of cost, schedule and performance. Some constraints were directed by the stakeholder (i.e., schedule deadlines), while others were derived from research and available data. The stakeholder reviewed and documented the limitations, then agreed on the project definition moving forward.

#### ***a. Cost Constraints***

As this is an integration case study, there are no cost constraints.

#### ***b. Schedule Constraints***

As this is an integration case study, there are no schedule constraints.

***c. Performance Constraints***

Performance constraints can be sub-divided into three categories: scope, quality, or technology (Kerzner 2013).

For the scope of threat engagement, the stakeholder provided the following vignettes:

- Solution for defense against small boats (FAC-FIAC/Bab al-Mandab)
- Solution for defense against C-802 Styx-like, sub-sonic missile
- Address vignette for LPD off the coast of Syria without DDG escort

**D. SYSTEMS ENGINEERING PROCESS**

The project team adopted a systems engineering (SE) process to complete this project and meet stakeholder requirements. The process outlined in Figure 4 shows the high-level process that the team followed to conduct the HEL integration concept study for LPD 17 class ships. The process focuses on effectively analyzing the integration concepts for potential use by the Navy.

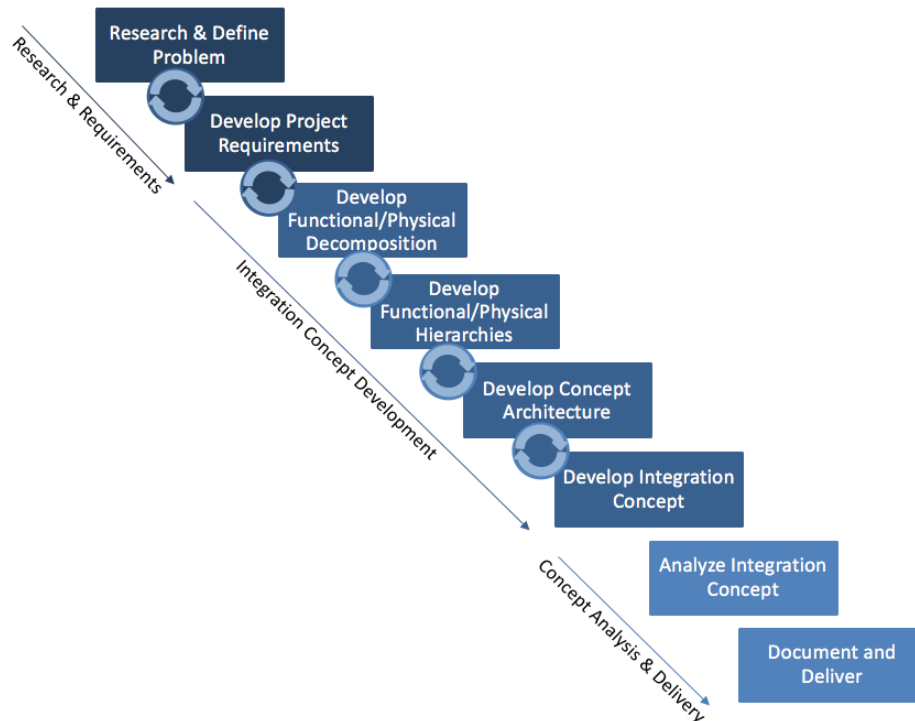


Figure 4. Systems Engineering Process

## 1. Research and Requirements

The first phase includes the steps: research and define problem and develop system requirements. Thus, logically, the phase begins with research and ends with a set of system requirements.

### *a. Research and Define Problem*

The process begins with the identification of stakeholders and initial team building between the project team and the stakeholders. Team building included derivation of the stakeholder's primitive needs. The project team conducted research to expand upon the statement of work, and draft an initial statement of the problem based on the stakeholder's needs. The team conducted further research to express the stakeholder's primal needs and refine the problem statement. After the team presented the revisions to the stakeholder, everyone agreed with the updates, and then finalized the problem statement. The consensus by the stakeholder led to the next phase of requirements development.

***b. Develop System Requirements***

Research and stakeholder input aided in the development of system requirements for the integration concept study. The team expected the basic system requirements to be sufficient for understanding the framework and guiding the process of integration analysis; however, modifications occurred where required.

**2. Integration Concept Development**

Following the definition of the requirements for the project, the next phase was to develop a concept for the integration of the HEL system onto a baseline platform, the LPD 17. The integration concept lays the groundwork for the transition to integrate HELs onto other naval platforms.

This phase incorporated the four central steps of the process: develop functional/physical decomposition, develop functional/physical hierarchies, develop concept architecture, and develop integration concept. These steps connect in series and represent an iterative feedback loop to illustrate the ability to revise the previous step.

***a. Develop Functional / Physical Decomposition***

Given the results of initial research and requirements development, the systems of interest needed an expanded view to understand the nature of the integration. Functional and physical decompositions are similar other than that one focuses upon the system functionality and the other on the physical features. They both require identification and expression of these key items from the top-down. Each function and physical feature is deconstructed into its subsequent lower level functions and features. This continues until the purpose is met, or there are no more functions or features. This results in a functional decomposition and a physical decomposition each.

Once the team decomposed the HEL and LPD 17 characteristics within the larger, overall system context, the process continued towards the creation of functional and physical hierarchies.

***b. Develop Functional / Physical Hierarchies***

With the understanding of the stakeholder's needs and the requirements and functional/physical decompositions completed, the team needed to develop functional and physical hierarchies. Development of the functional and physical hierarchies follows suit from the completed decompositions and moving from the top-down, beginning with the uppermost function and feature, connects each with the next lower level function(s) and feature(s). Each function or feature may have multiple lower-level children, but only a single higher-level parent. This is complete when all previously decomposed functions and features have been placed within the specific hierarchy in development. The team thus determined relationships between the functional and physical aspects of the to-be integrated system and created 1) a hierarchy of the functions that result from the integration and 2) a hierarchy of the physical aspects of the two integrated systems. These hierarchies informed the development of an architecture, which underlies the integration concept.

***c. Develop Concept Architecture***

The concept architecture guided the integration concept development for a HEL onto an LPD 17 class ship. The concept architecture illustrated the requirements as outlined by the stakeholder. The architecture further enabled the development of an integration concept by providing views or perspectives for different segments of the to-be integrated system. This helped to identify where tradeoffs may be necessary and whether they are feasible.

The architecture highlighted the interfaces for the concept that drives the HEL integration. Available SWAP-C characteristics for the LPD 17 were used with the architecture to align the integration concept with system requirements. This facilitated the understanding of the system requirements in terms of the SWAP-C characteristics, and thus informed the integration concept development.

***d. Develop Integration Concept***

The team developed an integration concept to serve as a blueprint for the integration of a HEL and its subcomponents onto an LPD 17 class ship. The HEL and ship class

characteristics, related through the architecture, helped develop the integration concept for to ensure compliance with system requirements. The integration concept included the description of an evaluation method for assessing potential integration solutions. During development of the integration concept, the team considered HEL component placement in order to identify integration considerations that may influence HEL performance. Understanding these integration considerations and their potential impact on a successful integration and applying them through the evaluation method is critical and was the focus of the next step, analyze integration concept.

### **3. Concept Analysis and Delivery**

The final phase includes the steps: Analyze integration concept and document and deliver. The first step in this phase applies the integration concept developed in the previous phase and analyzes its effectiveness in meeting the system requirements. The second step is self-explanatory. Concept analysis and delivery are connected in series with the preceding two phases, with no iterative or feedback relationship.

#### ***a. Analyze Integration Concept***

After the team created HEL and LPD artifacts, the integration concept was developed. The team examined the architecture and concept for integrating the HEL onto the LPD 17. In this part of the SE process, the team analyzed the concept developed in the previous step to ensure the system integration is designed to achieve its desired performance capabilities against the identified threats.

Recognizing that limited scope and time prevented capturing of system characteristics, developing performance objectives traceable to the system requirements, drafting of scenarios and proper conduct of performance analysis versus each threat, it was decided to focus on higher-level integration decisions and how those decisions may influence performance. First among high-level decisions are component placement including SWAP-C factors and topside integration or suitability thereof.

The team decided to use scale ship drawings to identify placement alternatives for the HEL components following logical limits on space available and nominal tactical

positioning with respect to the coverage desired. An evaluation of alternatives approach was selected for analyzing the placement alternatives based upon a set of evaluation criteria developed with traceability to system requirements.

Once the team completed the evaluation, the results provided a ranked list of placement alternatives. Final analysis required examination of the ranking values against applicable integration considerations to arrive at a recommendation for the best placement alternative.

***b. Document and Deliver***

Once the analysis was completed, the team consolidated their findings into this report. The best placement alternative was recommended with justification/explanation related to various integration considerations. Ideas for further study or expansion of the analysis were included for future consideration.

**E. SUMMARY**

Integration of new and developing weapon system technologies are important to the U.S. Navy in meeting its mission effectiveness, while maintaining an advantage over its adversaries in the battlefield environment. To that end, having a viable integration concept aids the Navy in achieving that goal. The project SE process lays the groundwork for accomplishing this objective.

## II. RESEARCH AND REQUIREMENTS

According to the SE process detailed in Chapter I, the first steps are to research and define the problem and develop the system requirements, as shown in the shaded section of Figure 5. This research helped define the understanding of naval platform integration challenges and bring the problem definition to realization. To do this, the team identified the stakeholders as those who have an active interest in the outcome. The Commander, Naval Surface Forces, Atlantic (N8) was found to be sole stakeholder for this project. The team elicited their needs via a collaborative stakeholder briefing. These primitive needs provided essential information to help fully comprehend the problem definition and requirements. This chapter will further discuss both the problem definition and requirements.

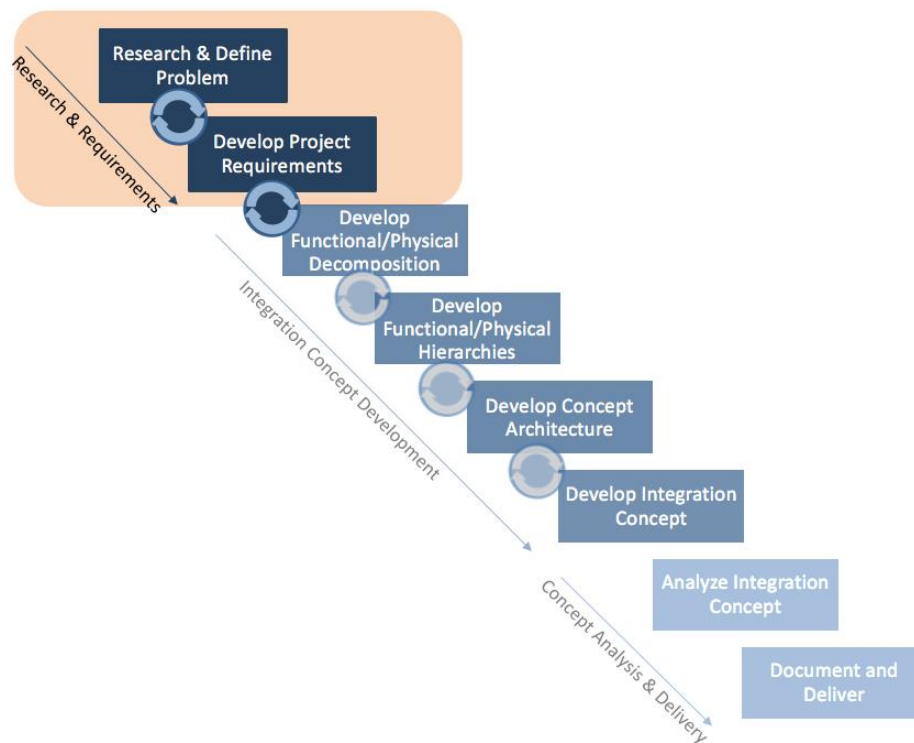


Figure 5. Systems Engineering Process (research and requirements phase)

To understand the system and its interactions, a context diagram was developed depicting external interactions as well as inputs and outputs to and from those external factors; this is called a context diagram and is shown in Figure 6. At the center of the context diagram is the HEL system. The LPD factors are to the right and other external factors are to the left. The HEL's inputs and outputs are directional either to or from the external factors.

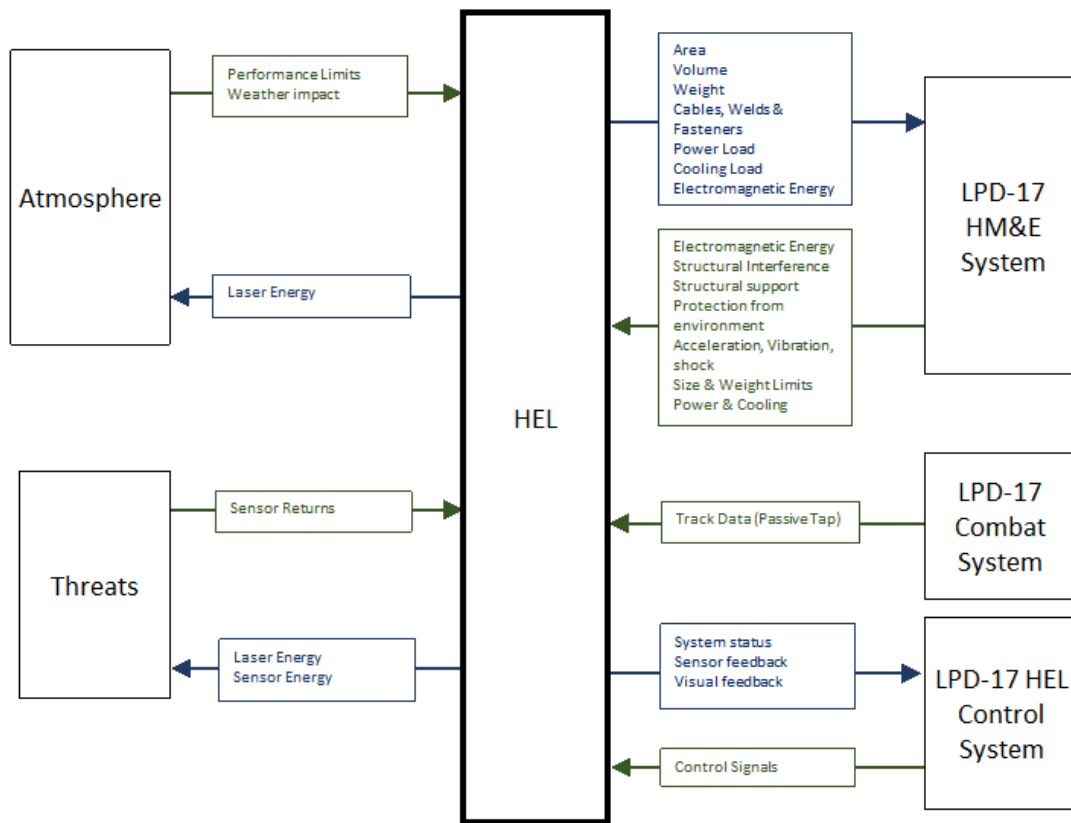


Figure 6. HEL context diagram

The HEL system interacts with the atmosphere, LPD, and its threats. Since the HEL interacts differently with subsystems of the LPD, they were broken into multiple boxes with differing inputs and outputs. Understanding these interactions was key to integrating two systems since these factors define and characterize cost, schedule, and technical requirements.

As the HEL interacts with the LPD Hull Mechanical and Electrical (HM&E) system, it is providing things like weight, cables, and electromagnetic energy that the HM&E system needs to be able to accommodate. In turn, the HM&E system provides factors such as structural interference, protection from the environment, and vibration and shock that the HEL system will need to accommodate as well. As the HEL system interacts with the LPD combat system, the HEL system is receiving tracking data, and providing no inputs to the LPD combat system itself. As the HEL system interacts with the LPD HEL control system, it provides the system status and any current error messages along with sensor and visual feedback. In turn, the LPD HEL control system provides control signals such as applying additional power when the HEL system status requires it. In this interaction, the LPD HEL control center must be able to take the HEL system's outputs and turn them into the actions it requires to function.

As the HEL interacts with the environment, it is subject to the various weather phenomena. Rain, snow, smog, fog, humidity, and temperature all have an effect on the HEL's performance. The HEL's performance is dependent upon the weather and its atmospheric effects. Anything in the laser beam's path such as evaporated sediment or salt scale on a lens subjects the system to serious damage and/or destruction while the laser is emitting such high and concentrated energy.

Once the HEL receives track data from the combat system and slews to a threat, the HEL sensors (cameras) begin providing imagery and data such as size, speed, and range of the threat. When the decision is made to fire the HEL, the laser's beam will strike a small spot on the target with the intent being to burn through the surface to damage airworthiness, cause explosive materials to explode, and/or cause damage to internal controls.

## **A. STAKEHOLDER ANALYSIS**

Stakeholder inputs provided a sufficient set of primitive needs for guiding initial work. The team continued to interact with the stakeholder throughout the project to receive additional project information and clarification. Additionally, the team received stakeholder feedback throughout the project.

## **1. Stakeholders**

The stakeholders included active duty military and civilian government employees who sought a solution to the integration of a HEL onto a naval surface platform as well as the operational commands and personnel who will benefit from employment of an integrated HEL weapon system's capabilities. The primary stakeholder, Commander Naval Surface Forces Atlantic, identified CAPT Kyler as the point of contact (POC). The requirements originated from this office and then disseminated to the appropriate levels of government to meet the fleet's needs.

## **2. Stakeholder Needs**

The team's primary focus centered on an unescorted LPD 17 class warship in an asymmetric threat environment. The stakeholder established that the HEL must defend the ship against unmanned aircraft systems (UAS), swarms of small boats, and subsonic anti-ship cruise missiles (ASCM) similar to the C-802 "Styx" missile. To defend against these threats, the HEL placement needed to maintain 360° weapon coverage with two mounts or greater than 180° with a single mount, as well as an elevation from just below the horizon up to the zenith (-5° to 90°). The intent being to enable the HEL the capability to defend the ship against asymmetric threats from any incoming axis. Additional needs elicited from the stakeholder included a partial integration with the LPD 17 combat system (SSDS Mk II) to provide "slew to cue" functionality or basically use the ship's combat system for obtaining and passing targeting data to the HEL in support of defensive engagements. The primary stakeholder sought an "art of possible" solution for immediate implementation.

For the past decade and a half, U.S. naval forces have increased their presence and operational tempo within the Fifth Fleet area of responsibility (AOR). The LPD 17 is an amphibious transport dock with a need for more self-defense capability. The stakeholder expressed that the integration of a HEL would increase this capability for self-defense. Specifically, the threats from UAS, FAC/FIAC, and ASCM are of great concern to units operating independently in the Fifth Fleet AOR. This capability would also serve as a unique asset to an Amphibious Ready Group (ARG) or Expeditionary Strike Group (ESG). An LPD 17 with an integrated HEL would increase self-defense capability, capacity, and

flexibility for any group to which the LPD belongs and potentially free-up Cruiser-Destroyer (CRUDES) assets typically assigned as ARG / ESG escorts, so that their other warfare area capabilities (such as anti-air warfare or anti-submarine warfare) may be leveraged more effectively than when tied to an ARG or ESG.

The Navy Laser Family of Systems (NLFoS) Rapid Prototyping, Experimentation and Demonstration (RPED) includes, but is not limited to, the following current laser weapon system efforts: surface Navy laser weapons system (SNLWS), solid state laser technology maturation (SSL-TM), optical dazzling interdiction—Navy (previously referred to as low power module (LPM)), and the ruggedized high energy laser (RHEL) (Chief of Naval Operations 2017). A challenge for these HEL programs is the high cost of development; however, the placement of these four laser programs into the RPED acquisition speaks to the urgency of the Navy’s desire for integration of a HEL onto a naval surface platform. The RPED’s purpose is to “employ accelerated processes to respond to urgent operational needs...that require immediate actions to mitigate current threats or leverage advances in technology that will enable Naval forces to maintain their operational and technological superiority over potential adversaries” (Department of the Navy 2016). The rapid acquisition process is evident through the accelerated development of the LaWS and SSL-TM HELs and their respective at-sea demonstrations (LaWS on *USS Ponce* from 2014 through 2017 and SSL-TM installed on a representative LPD 17 class ship as early as the fall of 2018).

### **3. Stakeholder Analysis**

The problem statement endured many iterations because the objectives were not final. In coordination with the stakeholder, the project’s actual direction was realized. The iterative process allowed the team to research the current issues that face the naval surface fleet. Research topics included topside integration analyses, technical LPD papers, HEL historical and technical developments, and specific SWAP-C related analyses with additional focus on safety, HEL placement, interference, environment, and combat system integration.

The project team maintained a literature review catalog to define and refine applicable readings and sections for future reference and detailed important items such as title, author, problem statement, remarks/comments and potential use for particular SWAP-C definitions. The purpose of this catalog was to provide a short description of each team members' reading. The quick reference enabled team members to determine if the reading was applicable to their assigned subject area. As there were thousands of pages read, this was helpful in forming a baseline of system-specific and integration-related knowledge common across the project team membership.

As first envisioned, the problem statement would be a generic issue currently facing the Navy, that of integration of HEL weapon systems onto warships. The original plan for the project was to encompass this generic view in terms of both HEL and warship characteristics. However, upon further thought and discussion with the advisors and stakeholder, it was determined that a specific class of ship, the LPD 17, would provide a better focus for the integration analysis. The change in direction aligned better with the stakeholder's urgent operational need.

One of the team's primary concerns was the topside integration (including placement) of the HEL upon the LPD 17 platform. This required using scale ship drawings and information to see where the HEL can and should be installed, supported, and effectively employed. While the initial focus of the effort was on SWAP-C requirements, it also addressed other integration challenges such as maintaining pre-existing host platform capabilities, achieving desired HEL performance, and managing the related tradeoffs.

The first ship class chosen for HEL integration was the LPD 17 because of its presumed suitability. The HEL will be an addition to self-defense, such as the 30 mm gun, without displacement of current capabilities. A HEL will also provide additional area-defense for countering threats, and the capability for long-range positive hostile identification (Flatley and LCDR Pilkerton 2017). As shown in Table 1, a study of the LPD class ship found the integration of the HEL and its below deck equipment to have only minimal or moderate impacts to the ship's distributive systems (Flatley and LCDR Pilkerton 2017).

Table 1. Conclusion from HII Study of SSL-TM's Integration Impact to Below Deck Equipment on the LPD 23. Source: Flatley and Pilkerton (2017).

| <b>Equipment</b>                  | <b>Impact</b> |
|-----------------------------------|---------------|
| Arrangement and structure         | Moderate      |
| Combat system                     | Negligible    |
| HVAC / CW                         | Moderate      |
| Cooling plants                    | Negligible    |
| Weights and moments               | Minimal       |
| Electrical power and distribution | Minimal       |

An additional intention also existed to capture lessons learned and consider implications for cases of other HEL weapon systems integrated onto the LPD, as well as HEL integration onto other naval surface platforms. The goal was to highlight the most significant considerations and include some degree of prioritization where it was feasible and added value, to inform real-world integration efforts. In the end, a proper HEL integration effort should provide LPD 17 class ships with the needed capability, given the state of the art.

## **B. REQUIREMENTS**

The initial efforts at obtaining, understanding and leveraging stakeholder needs led to a relatively simplistic set of draft system requirements. These draft system requirements were useful for guiding early progress, but, through iteration, they were refined. At this stage, they became integration requirements. The reason for this - the effort was not a full integration effort, but rather an integration concept study. The effort was also not an acquisition or design effort. Using the phrase integration requirement tended to keep the effort better focused. This focus kept both LPD and HEL systems within the field of view, forcing consideration of both along with their boundaries and interfaces, throughout the effort.

To understand the integration requirements and terminology associated with them as listed in Table 2, the following definitions are provided:

“Some common ship kill definitions (in order of decreasing severity) are:

- Total Kill: Ship is lost entirely because sinking occurs or fire (or other phenomenon) forces abandonment
- Mobility Kill: immobilization or loss of controllability occurs
- Mission Area Kill: Particular ship mission area (e.g., anti-air warfare) is lost
- System Kill: Damage to one or more components or results in loss of a system.” (Calvano and Ball 1994, 73)

The team modified these definitions to make them applicable to the integration requirements.

- (1) For airborne threats, as adapted from Calvano and Ball (1994),

Total Kill: Threat Target is lost entirely because damage from fire or explosion (or other phenomenon) degrades airworthiness sufficiently to force it out of the sky;

- (2) For waterborne threats, as adapted from Calvano and Ball (1994),

Total Kill: Threat target is lost entirely because sinking occurs or fire (or other phenomenon) forces abandonment (if manned, the equivalent if unmanned);

- (3) For airborne and waterborne threats, as adapted from Calvano and Ball (1994),

Mobility Kill: threat target immobilization or loss of controllability occurs;

System Kill: damage to one or more components of the threat target results in loss of a system (such as sensor or propulsion);

Determination of values for probability of kill (Pk) and depression angle is beyond the scope of this project. They would be determined through analysis by proper authority in the case of an actual integration effort.

The integration requirements are provided in Table 2.

Table 2. Integration Requirements

| Requirement Number* | Requirement                                                                                                                                                                                                                                                                                                                          | Notes                                                                                                                                                                                                          |
|---------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| R1                  | The integrated HEL shall be capable of achieving a mobility kill versus a single hostile Unmanned Aircraft System (UAS).                                                                                                                                                                                                             | As adapted from Calvano and Ball (1994), Mobility Kill: threat target immobilization or loss of controllability occurs.                                                                                        |
| R2                  | The integrated HEL shall be capable of achieving a mobility kill versus up to X simultaneous hostile Unmanned Aircraft Systems (UASs).                                                                                                                                                                                               |                                                                                                                                                                                                                |
| R3                  | The integrated HEL shall be capable of achieving a mobility kill versus a single hostile small boat.                                                                                                                                                                                                                                 |                                                                                                                                                                                                                |
| R4                  | The integrated HEL shall be capable of achieving a mobility kill versus up to X hostile small boats.                                                                                                                                                                                                                                 |                                                                                                                                                                                                                |
| R5                  | The integrated HEL shall be capable of achieving a total kill versus a single hostile sub-sonic, anti-ship missile.                                                                                                                                                                                                                  | As adapted from Calvano and Ball (1994), Total Kill: Threat Target is lost entirely because damage from fire or explosion (or other phenomenon) degrades airworthiness sufficiently to force it out of the sky |
| R6                  | The integrated HEL shall meet specified reliability requirements assigned to the HEL design without degradation due to integration decisions.<br>(i.e., if the HEL, as designed, had and met a requirement for Operational Availability ( $A_o$ ) prior to integration, then it shall continue to meet that value after integration) | Reliability                                                                                                                                                                                                    |
| R7                  | The integrated HEL shall meet specified maintainability requirements of the HEL as designed, not to be eased or degraded by integration decisions.                                                                                                                                                                                   | Maintainability                                                                                                                                                                                                |
| R8                  | The integrated HEL shall include protection of vital components from                                                                                                                                                                                                                                                                 | Survivability                                                                                                                                                                                                  |

| <b>Requirement Number*</b> | <b>Requirement</b>                                                                                                                                                                                                                       | <b>Notes</b>                                                                                                                                                                                      |
|----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                            | effects of hostile weapons (blast waves, fragmentation, directed energy, etc.)                                                                                                                                                           |                                                                                                                                                                                                   |
| R9                         | The integrated HEL shall be positioned and installed in a manner to minimize effects of shipboard operations (shock, vibration, and others)                                                                                              |                                                                                                                                                                                                   |
| R10                        | The integrated HEL shall be positioned to minimize effects of turbulence.                                                                                                                                                                |                                                                                                                                                                                                   |
| R11                        | The integrated HEL shall be positioned and installed to minimize maritime environmental effects.                                                                                                                                         |                                                                                                                                                                                                   |
| R12                        | The integrated HEL shall comply with dimensional constraints of the space designated for it and/or its components based upon placement decisions made in support of the integration.                                                     |                                                                                                                                                                                                   |
| R13                        | The integrated HEL shall comply with the weight allowance/budget allotted per component as specified in the HEL-LPD Integration ICD.                                                                                                     |                                                                                                                                                                                                   |
| R14                        | The integrated HEL and its components shall comply with stability and righting moment limitations as prescribed in the HEL-LPD Integration ICD.                                                                                          |                                                                                                                                                                                                   |
| R15                        | The integrated HEL shall operate when provided with power in accordance with the HEL-LPD Integration ICD.                                                                                                                                |                                                                                                                                                                                                   |
| R16                        | The integrated HEL shall operate when provided with chilled water in accordance with the HEL-LPD Integration ICD.                                                                                                                        |                                                                                                                                                                                                   |
| R17                        | The integrated HEL shall be capable of slewing and acquiring an initial target track when provided with LPD target track data from the SSDS Mk II combat system. Engagement hand-off will be conducted in accordance with SSDS doctrine. | Analysis needed to determine the timelines before knowing specific solutions to this requirement is outside the scope of this case study and would be performed for an actual integration effort. |
| R18                        | The integrated HEL shall comply with the HEL-LPD Integration ICD specifications with regard to prevention of mutual                                                                                                                      |                                                                                                                                                                                                   |

| <b>Requirement Number*</b> | <b>Requirement</b>                                                                                                                                    | <b>Notes</b>                                                                       |
|----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
|                            | interference across the electromagnetic spectrum between itself and other LPD systems.                                                                |                                                                                    |
| R19                        | The integrated HEL must provide for tactical point-to-point voice communications between the TWC and CIC, and the TWC and Bridge.                     |                                                                                    |
| R20                        | The integrated HEL shall be capable of a maximum effective range greater than 3000 yards/2745 meters.                                                 |                                                                                    |
| R21                        | The integrated HEL shall be capable of providing azimuthal coverage of 360° relative for two mounts or greater than 180° relative for a single mount. | Coverage is to be provided out to maximum effective range or greater in all cases. |
| R22                        | The integrated HEL shall be capable of providing -5° to 90° coverage in elevation.                                                                    |                                                                                    |

### **C. SUMMARY**

In summary, researching and defining the problem statement and defining the system requirements have worked in tandem to fully scope the project. The upfront work created the project foundation; a basis for future integration and analysis efforts. The system requirements developed during the first phase of the SE process and discussed in this chapter will be useful in developing functional and physical decompositions and a high-level operational viewpoint (OV-1) diagram. These tools are useful because they illustrate the relationships that exist for a laser integration. These relationships will be used to determine where trade-offs will be necessary when integrating the HEL with the ship's current systems. With this foundation applied, the next step towards the development of the integration concept, decomposing the project components, can begin.

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### III. INTEGRATION CONCEPT DEVELOPMENT

The completed research and requirement phase provided the system requirements as input to the next phase of the SE process, developing the integration concept. The output of which was a set of artifacts and an evaluation method that formed the foundation of the integration concept. Figure 7 illustrates the integration concept development phase broken down into four steps.

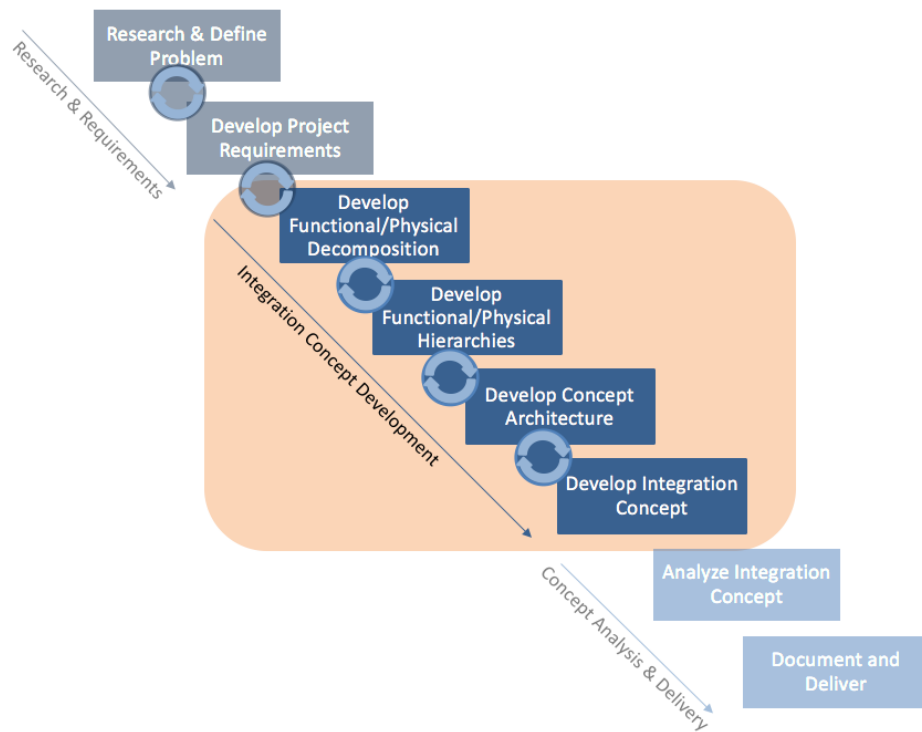


Figure 7. Integration Concept Development Phase

#### A. FUNCTIONAL ANALYSIS

Functional analysis is a methodology to transform the system requirements into system functions (Defense Acquisition University 2001). In this study, functional analysis involved the functional and physical aspects of the HEL and the LPD 17 class ship. Functional and physical decomposition were performed in a more generalized fashion than

Whitcomb and Szatkowski (2000) describe due to the nature of this study. Once these were understood, they were then leveraged in developing the concept architecture.

A useful tool to organize large-scale systems into manageable subsystems is decomposition. Using decomposition, a system can be broken down into any number of logical subsystems arranged in a hierarchy that defines the interconnections among the subsystems. The hierarchy maintains the structure of the system through subsystem interconnections. (Whitcomb and Szatkowski 2000)

### **1. Functional Decomposition**

The functional decomposition consists of the top-level functions of the integration of the HEL on the LPD 17 class ship, as shown in Figure 8. The primary function of the HEL is to defend the LPD 17 class ship against single or multiple threats, which is at the top of the hierarchy. The HEL achieves its secondary functions at the next level. These functions include acquiring and tracking multiple targets, providing counter ISR, engaging threats, assessing engagement effectiveness, and support operations.

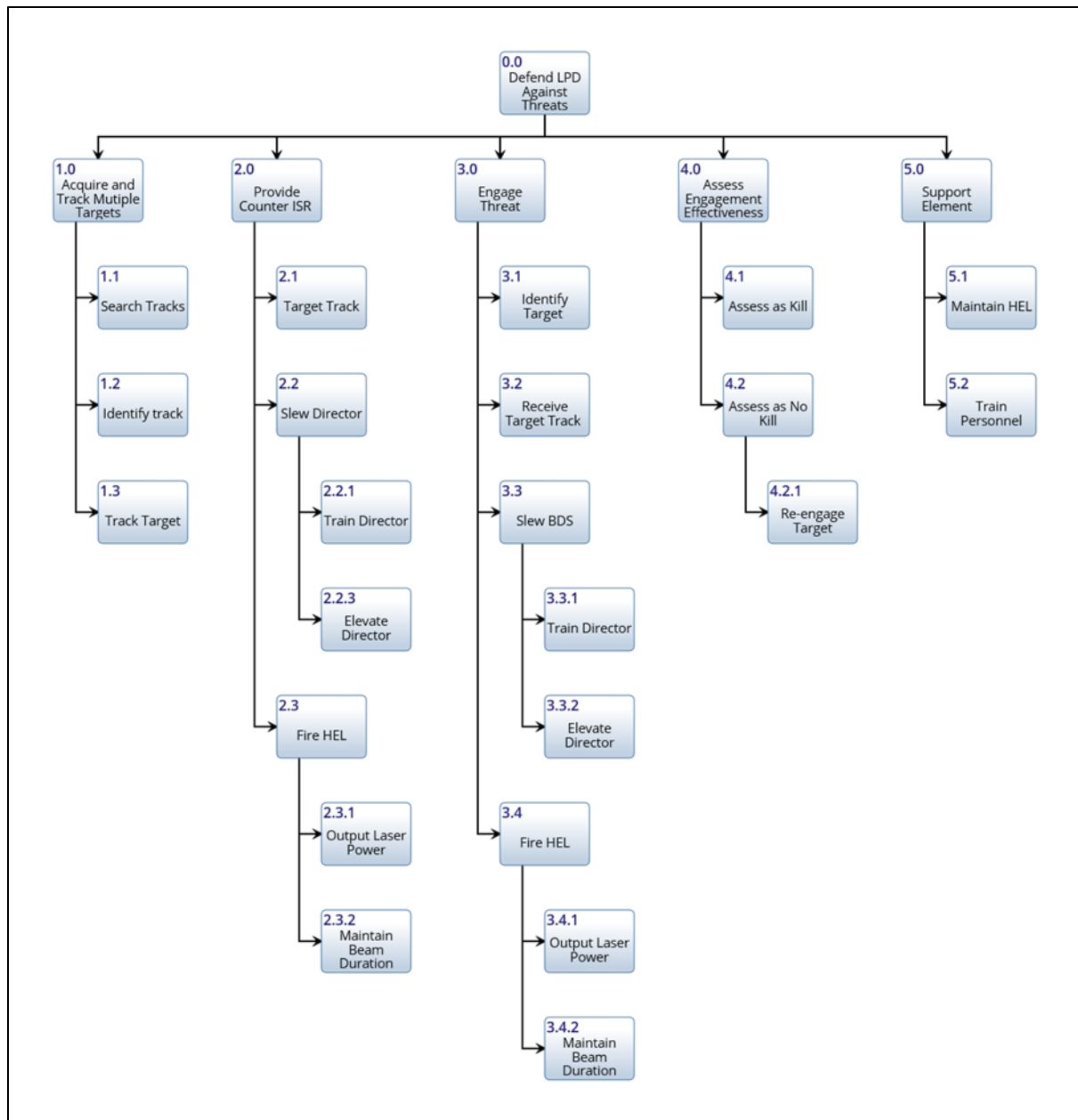


Figure 8. Functional Decomposition - Integrated LPD and HEL

The functional decomposition of the LPD and HEL distinguish the key differences between functions of both the HEL and the combat system (SSDS MK II). The SSDS MK II three-dimensional air search radar acquires and tracks targets of concern, then interfaces with the HEL. The SSDS MK II provides target data so the HEL can carry out engagements. The Tactical Action Officer (TAO) coordinates with the Laser Weapons

Console (LWC) Operator for intent and execution of orders on potential threats. Intent and execution are determined by specific parameters of the threat, environmental considerations, and the specific tactical situation of the ship.

When conducting counter ISR, the HEL can dazzle the target as an indication of warning and intent. Another option is to engage the threat if it meets criteria determined by the Commanding Officer through the TAO. The HEL will target the threat, create an engagement, and slew the beam director to engage the threat. A battle damage assessment follows the engagement and determines success or failure with the option of re-engaging if deemed a “No Kill.” The key to classifying a dazzle versus an engagement is with the specifics of power output and duration of the beam on the target. One of the major advantages of the HEL is scalability. Scalability is the ability to either illuminate the target or destroy it while using the same system and engagement solution by varying the power output.

As with all weapon systems, the HEL must have support operations to maintain it and a way to train operators who use the system. The HEL will have various maintenance periods that must be de-conflicted and coordinated with the combat system’s maintenance in order to maximize the availability of the weapon system. The SSDS has the capability to participate in coordinated training using the Battle Force Tactical Training (BFTT) tool. It would be ideal if the HEL operator were able to place the HEL in a training mode and participate. A training mode would allow the HEL to conduct simulated engagements either organically or with the ship and other forces via BFTT. This is the most realistic approach to training the HEL operators.

## **2. Physical Decomposition**

The HEL weapons system physical decomposition categorizes the integration between the HEL and the LPD 17 class ship. Figure 9 shows the physical components of the LPD placed into their respective systems. The team identified two major physical systems for consideration. The hull, mechanical, and electrical (HM&E) and the combat system - Ship’s Self Defense System (SSDS) MK II.

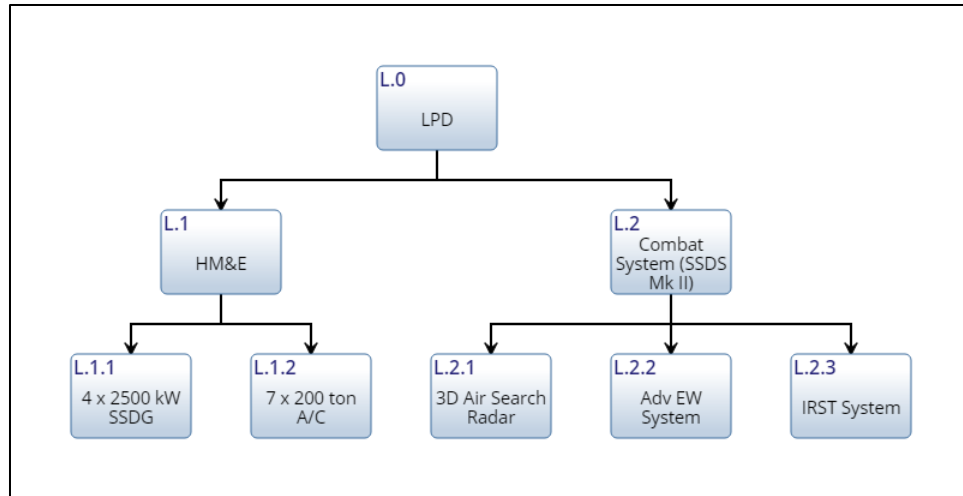


Figure 9. Physical Decomposition - LPD

The major components that make up the HM&E system include four 2500 kW ship's service diesel generators (SSDGs) and seven 200-ton air conditioning (A/C) units. The SSDGs and the A/C units combine to provide power and cooling for the HEL and its accompanying components. These two major components also account for two of four SWAP-C factors. The SSDS MK II is comprised of the three-dimensional air search radar, advanced electronic warfare (EW) system, and the infrared search and track (IRST) system. Together these three systems provide track data for use in HEL weapon system engagements. These physical components are part of the LPD 17 class ship for this integration.

The HEL weapon system has six primary components: The Tactical Laser Core Module (TLCM), Thermal Storage Module (TSM), Energy Storage Model (ESM), Laser Weapons Console (LWC), Combat System Integrated Support Equipment (CSISE), and Hybrid Predictive Avoidance Safety System (HPASS). Figure 10 illustrates the physical breakdown of the HEL system.

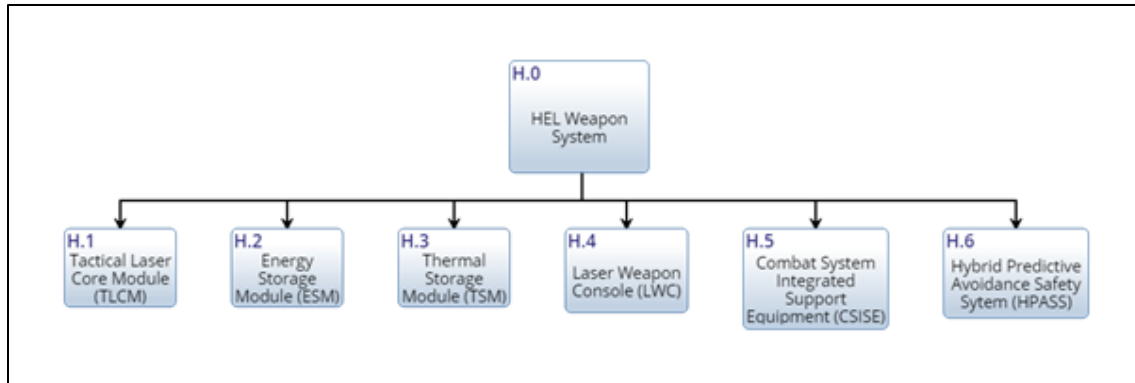


Figure 10. Physical Decomposition—HEL

The TLCM is the heart of the laser weapon system consisting of the general structure of the HEL and houses the beam director itself on a mount that provides for rotation and elevation as with traditional gun mounts. The ESM and TSM specifically support the HEL by ensuring that it receives the necessary power and cooling during critical situations. The LWC is in the Combat Information Center (CIC) and serves as the human-machine interface for the HEL weapon system (Flatley and LCDR Pilkerton 2017). The operator utilizes the LWC to control the HEL and generate engagements with supporting data from the SSDS combat system. The CSISE and HPASS are generally located near the LWC and serves as the primary interface center for the HEL and SSDS integration. The CSISE contains the software and networking construct necessary to integrate the HEL with the intricate combat system of the ship. The HPASS is a special component designed specifically to prevent interference with satellites and other ship assets. The HPASS also ensures maximum safety around the ship and to personnel near the HEL. These six major components make up the HEL weapon system and are crucial for operating the HEL safely and in harmony with the ship's systems.

## B. DEVELOP CONCEPT ARCHITECTURE

The concept architecture is an aggregate of several viewpoints at the foundational level; it is the combined decomposition, hierarchies, and the integration requirements. To visualize the architecture, it was necessary to consider what was learned from the

assumptions and constraints bounding the integration problem first, weighed against that learned in the functional analysis.

Before one can identify locations and begin to consider whether space is available, it is critical to know how the components fit together. The distance allowed between HEL components may be constrained depending upon design factors. For example, if there are distance restrictions between component connections, the tactical laser core module (TLCM), energy storage module (ESM), and a thermal storage module (TSM) may have to be located in the same vicinity. In the case where the separation between components is feasible and the ship's internal spaces provide room for the ESM and TSM to occupy, the TLCM would be the only HEL component placed topside. These factors played a role when identifying alternatives for HEL placement. While the concept of placing the ESM and TSM internally was desirable, their height prevented fit on a typical deck or level and the only other possibility was to consider locations within the well deck. The decision was made to focus on the topside positions for all components.

Identifying placement possibilities first is important when integrating with an existing ship design. A ship's limited space is utilized to the maximum extent possible while providing necessary room for equipment, and work and living space for personnel. The introduction of a new system within an existing footprint may require modifications to uphold its structural integrity. Alternatively, a new system may require tradeoffs with current weapons systems and their associated capabilities. This was evident with the first alternative that the Navy proposed, which called for the placement of the HEL's components within space designated for the vertical launch system (VLS) on LPD 17 class ships. For the remaining alternatives, the team identified external locations to place the HEL components. The team considered the TLCM placement to maximize the effectiveness of the laser's coverage. One of the requirements placed upon the team was 180° coverage for one laser, and 360° for two lasers. Topside obstructions factored into the TLCM's placement depending upon how they detracted from the azimuth and elevation coverage.

The placement priorities depend upon the weapons system the Navy is willing to tradeoff for the HEL integration. The removal of an onboard weapons system will dictate

the need to analyze if the sacrifice degrades or improves capabilities. Multiple proposed alternatives did not require replacing an existing weapons system. The team sought to minimize impacts to the ships structure and existing systems. With this in mind, most alternatives utilized topside spaces exterior to the ship. As mentioned earlier, one HEL alternative occupied the VLS footprint onboard the LPD 17. Another alternative replaced the port side MK 46 30 mm machine gun on the O-4 level with the TLCLM. These alternatives are examples of the tradeoffs and sacrifices that need to be considered with any shipboard integration problem.

The eight placement alternatives are listed in Table 3 with placement descriptors, which help visualize their relative position on the LPD. The placement alternatives include four individual HEL placement options as single alternatives and four paired HEL placement options as dual alternatives. The coverage in azimuth and elevation for each alternative was an important decision-supporting feature for this integration concept. This report intentionally limited the elevation coverage for the eight placement alternatives to a single, directionally-oriented radial that runs from either the bow (for forward placement alternatives) or directly astern (for aft placement alternatives) beginning with the depression angle running up to zenith and then down again in elevation. There were an infinite number of radials ( $360^\circ$  and every, ever-increasing decimal subdivision between any two adjacent degrees) that could be defined for each placement alternative. Defining each of these points was beyond the scope of this effort, thus the coverage illustrations shows only a single representation.

Table 3. List of HEL Alternatives with Placement Descriptors

| <b>Alternatives</b> | <b>Placement Descriptors</b> |
|---------------------|------------------------------|
| A                   | Bow-Low                      |
| B                   | Bridge-High                  |
| C                   | Aft-Centerline               |
| D                   | Aft-Port                     |
| AC                  | Bow-Low, Aft-Centerline      |
| AD                  | Bow-Low, Aft-Port            |
| BC                  | Bridge-High, Aft-Centerline  |
| BD                  | Bridge-High, Aft-Port        |

The eight alternatives give the LPD 17 options to maximize defensive capabilities and satisfy SWAP-C factors while minimizing shipboard modifications, mutual interference, and possible integration conflicts. The single alternatives A, B, C, and D form the necessary initial building blocks for developing the integration concept. As individual HEL placement options, they bring at a minimum, additional defensive capability to the LPD. Should a second HEL be unsupportable in terms of SWAP-C factors, the choice must fall to one of the single alternatives. Dual alternatives AC, AD, BC, and BD are paired combinations of the individual alternatives. The purpose of the dual alternatives was to provide 360° in horizontal coverage (azimuth) around the ship, with 180° in vertical coverage (elevation) above the ship. The pictures provided in Figures 11 and 12 depict horizontal and vertical coverage, respectively. This complete coverage by the HEL encapsulated the ship within a sphere of self-protection. The addition of a HEL in a reasonable position offered additional self-defense capabilities to the ship; however, the capability benefits increased more as the physical blockage and electronic interference decreased. In general, the dual alternatives combined the benefits and mitigated the negatives faced by each individual alternative, thus maximizing the HEL's relative effectiveness. An example of this was utilizing alternative C versus alternative D for the aft HEL to avoid the stack exhaust to some extent. Conversely, alternative D might hold favor over alternative C because of the possible interference with the SPS-73 rotating surface radar. For the ship's forward alternatives, the Navy may decide to install VLS cells in the space reserved for their use and alternative A would no longer be an option. In this case, alternative B would be beneficial because the HEL and VLS are no longer mutually exclusive.

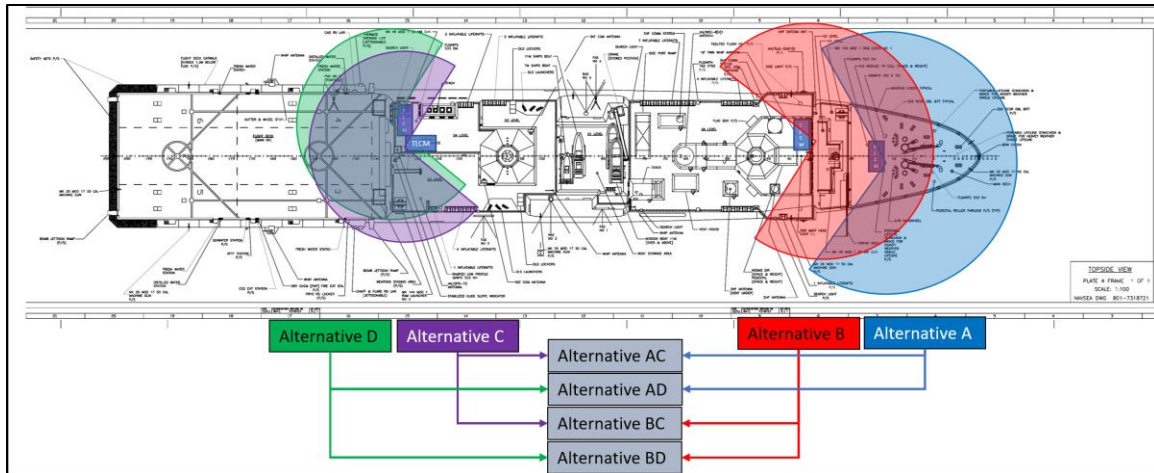


Figure 11. HEL Combination Alternatives—Azimuth Coverage

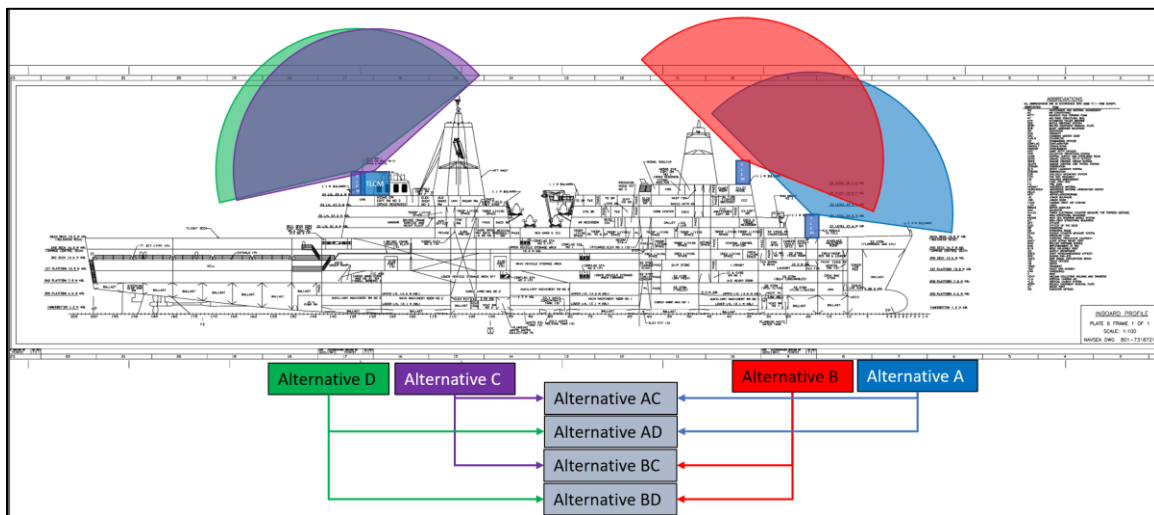


Figure 12. HEL Combination Alternatives—Elevation Coverage

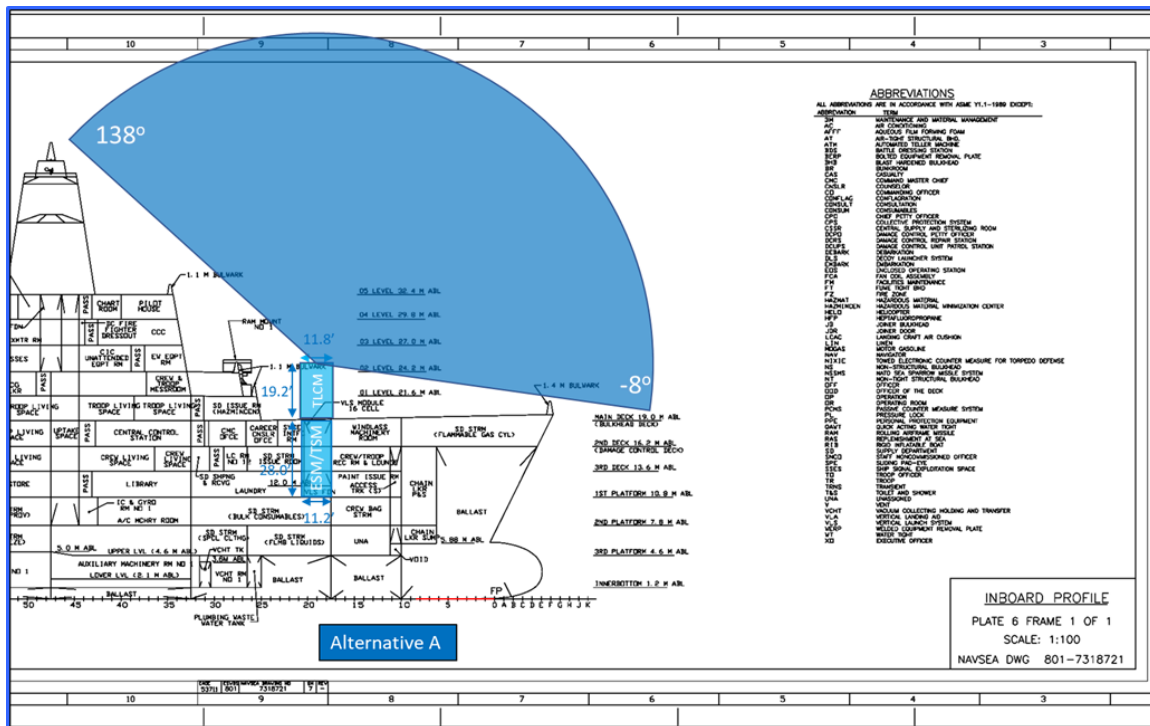
Lasers emit radiation by producing an intense, directional beam of light (United States Department of Labor, Occupational Safety and Health Administration n.d.). This dangerous emission of light is known as a radiation hazard (RADHAZ). For the ship's forward alternatives, the Navy may choose to use the VLS space for its intended purpose. In this case, alternative B would be beneficial because both the HEL and VLS capabilities are available. If RADHAZ was of concern with alternative B and the Navy does not plan to use the VLS, then alternative A would be the better option.

## **1. Alternative A**

Alternative A is the placement that the Navy is currently proposing for the SSL-TM testbed integration onto a representative LPD 17 class ship. The HEL would occupy the space currently reserved for VLS forward of the bridge including its existing footprint below decks. The ESM and TSM components required modifications from their original design to fit into the internal ship spaces. The ESM and TSM design allow for pre-assembly and installation into the ship. The installation will occur in two phases. The first phase will position the ESM, TSM, and the TLCM foundation into place. The second phase will be the installation of the TLCM top side, laser weapons console (LWC), and integration of the components (Flatley and LCDR Pilkerton 2017).

The azimuth ranges for alternative A used the ships bow, 000°R, as the starting reference point. The total azimuth coverage was 230°, which ranged from 250°R to 120°R. The total elevation coverage was 146°, and ranged from -8° to 138°. The elevation coverage measured along the laser's longitudinal axis from 8° below the horizon to zenith (directly overhead) and continued aft another 48°. The azimuth and elevation coverage arcs are two-dimensional simplifications that represent the HEL's three-dimensional motion. Figures 13 and 14 illustrate the horizontal and vertical coverage, respectively. With the HEL system inside the VLS footprint, minimum interference is present; however, could pose a risk to personnel on the forecastle if not secured during weapons use. These details will be determined in future studies that will investigate the hazards and identify risk mitigation measures.





## 2. Alternative B

Alternative B placed the HEL above the pilothouse of the LPD 17. The elevated position of the TLMCM relative to alternative A resulted in an expanded coverage both in azimuth and in elevation. The azimuth ranges for alternative B used the ship's bow, 000°R, as the starting reference point. The total azimuth coverage was 245°, which ranged from 225°R to 110°R. The total elevation coverage was 157°, and ranged from -22° to 135°. The elevation coverage measured along the laser's longitudinal axis from 22° below the horizon to zenith and continued aft another 45°. Figures 15 and 16 illustrate the horizontal and vertical coverage, respectively. This alternative's placement around multiple communications systems causes concern about possible transmission blockages. The external placement of all components also causes concern for increased radar cross section and will require additional passive control measures (PCMs) to address the increase. The location of the HEL components just above the pilothouse may introduce RADHAZ issues to personnel standing watch while on the bridge or as a lookout as well as mutual

interference and hazard concerns with existing ships electronic equipment and antennas in close proximity.

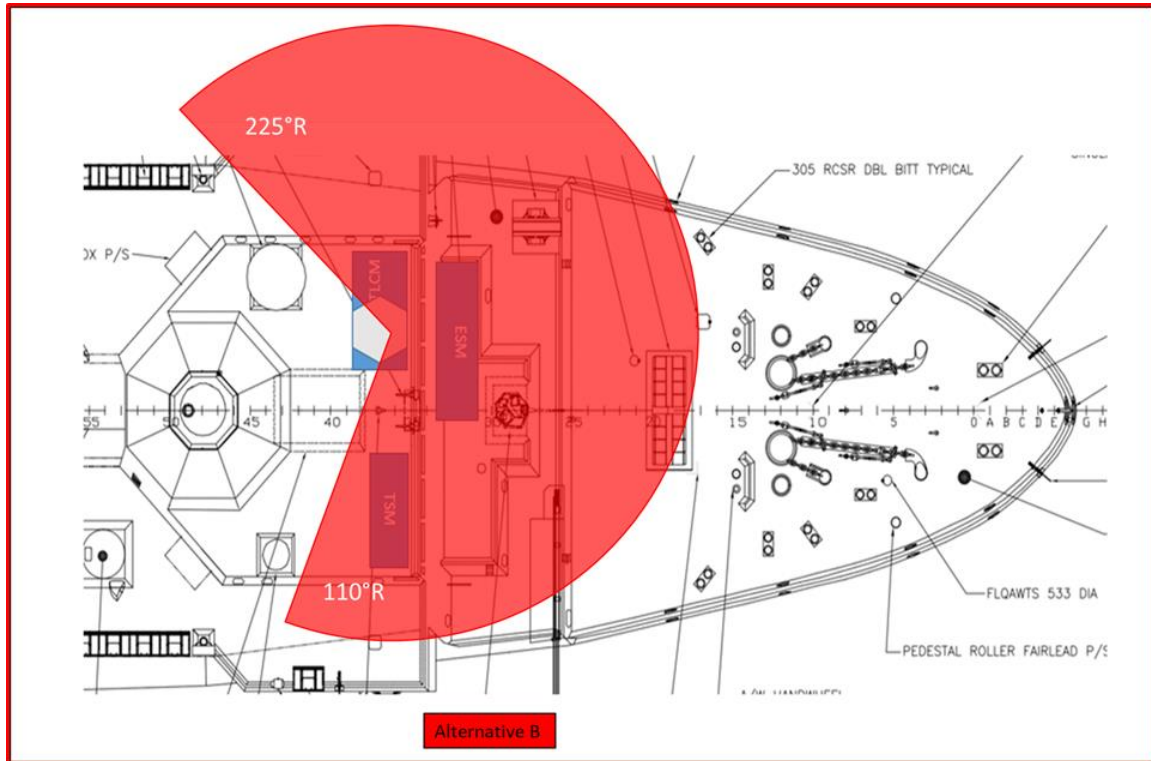


Figure 15. HEL Alternative B—Azimuth Coverage

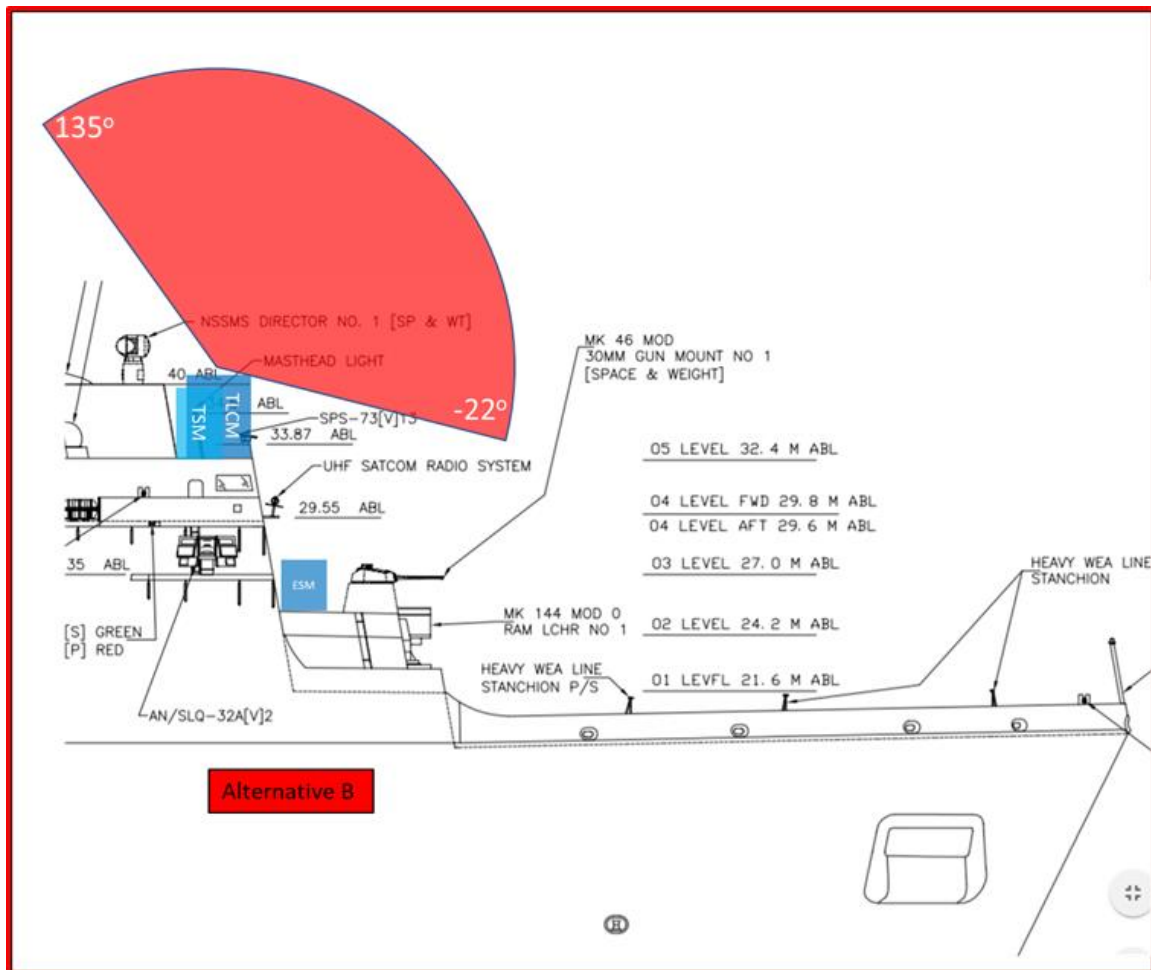


Figure 16. HEL Alternative B—Elevation Coverage

### 3. Alternative C

The azimuth ranges for alternative C used the ship's stern, 180°R, as the starting reference point. The total azimuth coverage was 250°, which ranged from 030°R to 280°R. The total elevation coverage was 151°, and ranged from -12° to 139°. The elevation coverage measured along the laser's longitudinal axis from 12° below the horizon to zenith and continued forward another 49°. Figures 17 and 18 illustrate the horizontal and vertical coverage, respectively. Alternative C took into consideration the effects of the stack gases by placing the TLCM near the centerline. This has the potential to minimize the effect of the exhaust gases on the HEL and affords the option of leaving the 30 mm gun weapon system in place. Placing the TLCM and its components near the centerline introduced the

risk of mutual interference between the HEL and the SPS-73 rotating surface radar. The SPS-73 is located on top of a box, centerline aft, and depending upon target positions, it could interfere with the HEL TLCM's operations. With a TLCM height higher than the radar, this should minimize any significant interference between the two.

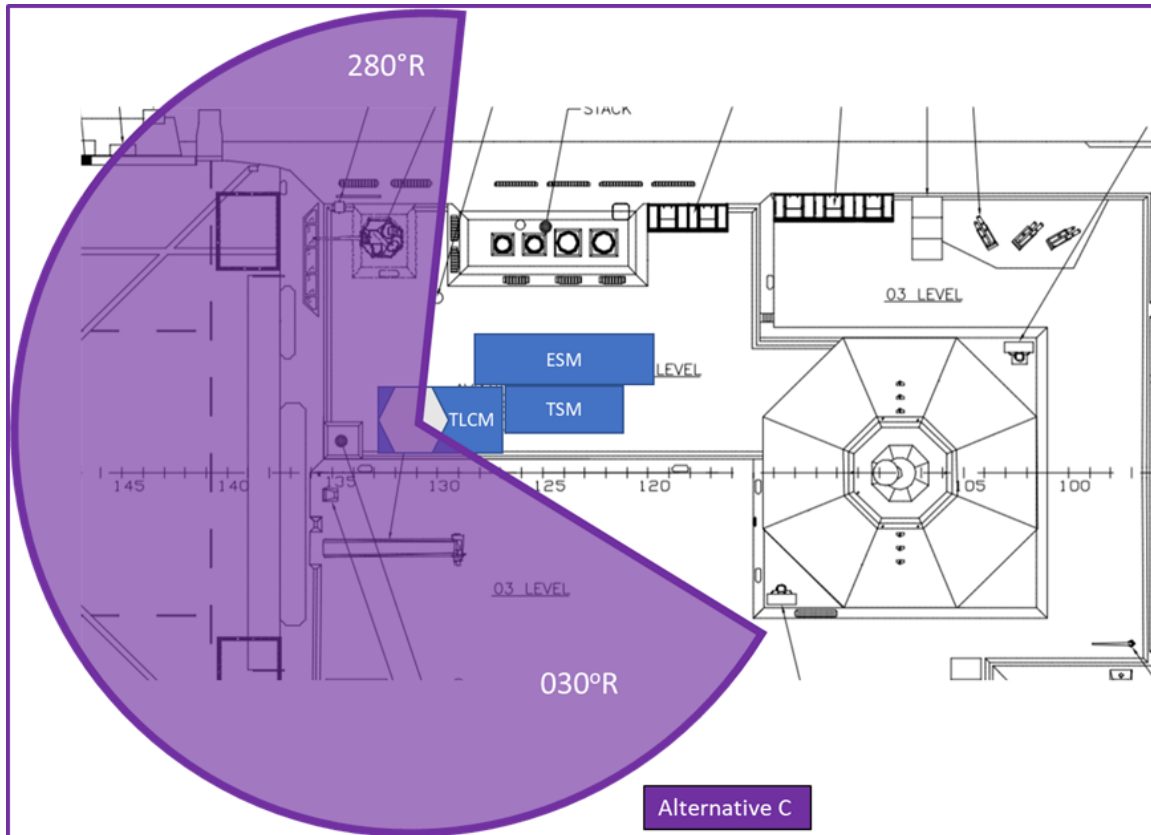
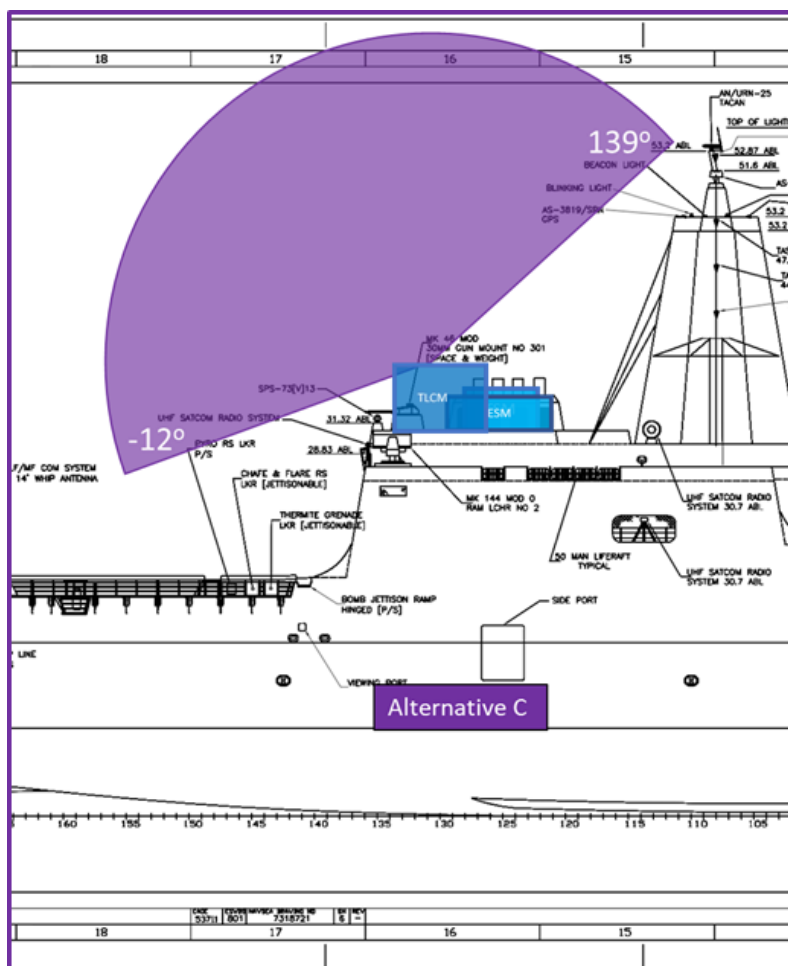


Figure 17. HEL Alternative C—Azimuth Coverage



#### 4. Alternative D

The azimuth ranges for alternative D used the ship's stern, 180°R, as the starting reference point. The total azimuth coverage was 270°, which ranged from 045°R to 315°R. The total elevation coverage was 156°, and ranged from -13° to 143°. The elevation coverage measured along the laser's longitudinal axis from 13° below the horizon to zenith and continued forward another 53°. Figures 19 and 20 illustrate the horizontal and vertical coverage, respectively. The original TLCM placement was in the footprint of the aft 30 mm gun mount. The first reason for this placement was that the HEL likely outperformed the gun. Another reason was that the gun mount's removal would make additional SWAP-C factors available to ensure support for the HEL. Some key items that were considered

with this alternative was the approximate location of the HEL in relation to the aft exhaust stacks. For a traditional kinetic weapon, the stack gasses and heat interference with the weapon is negligible; however, for this laser, the stack gases and excess heat could affect the HEL beam significantly due to turbulence. The ship's forward motion will cause the exhaust to drift aft, possibly enveloping the laser's line of sight. Future studies must analyze these effects on the laser's performance to understand the system limitations. In addition, the HEL LWC operator and TAO must be cognizant of any possible flight operations occurring on the flight deck below for both aft alternatives. Interference with the HEL and flight deck personnel or pilots could pose a safety risk.

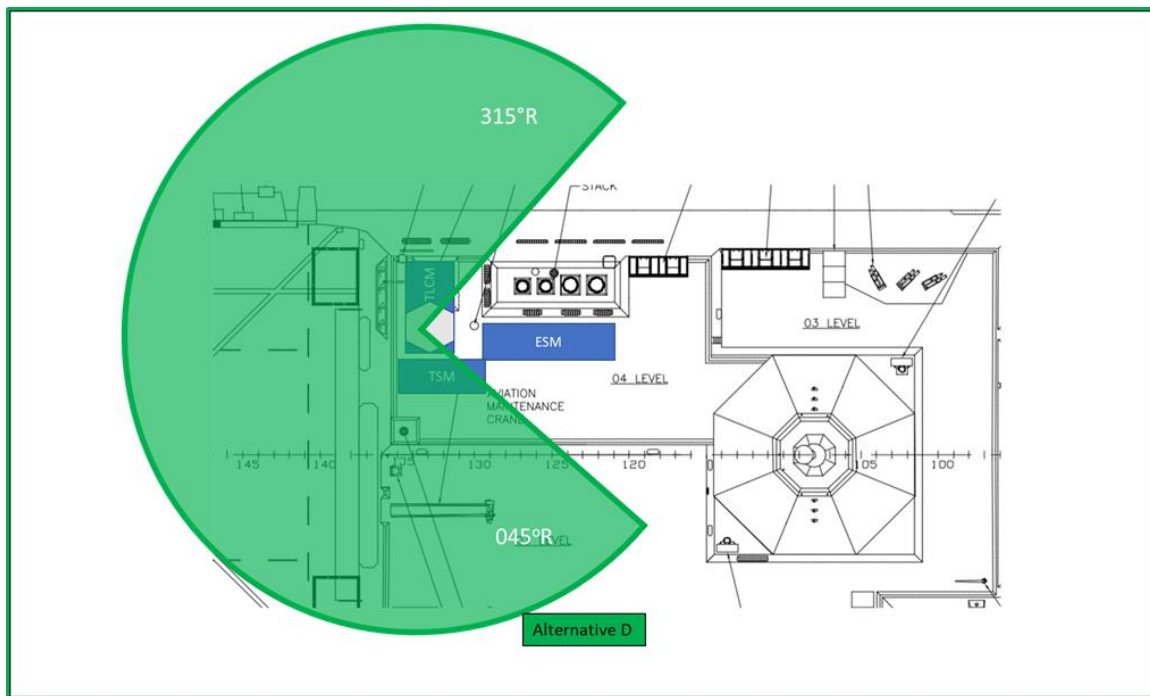


Figure 19. HEL Alternative D—Azimuth Coverage

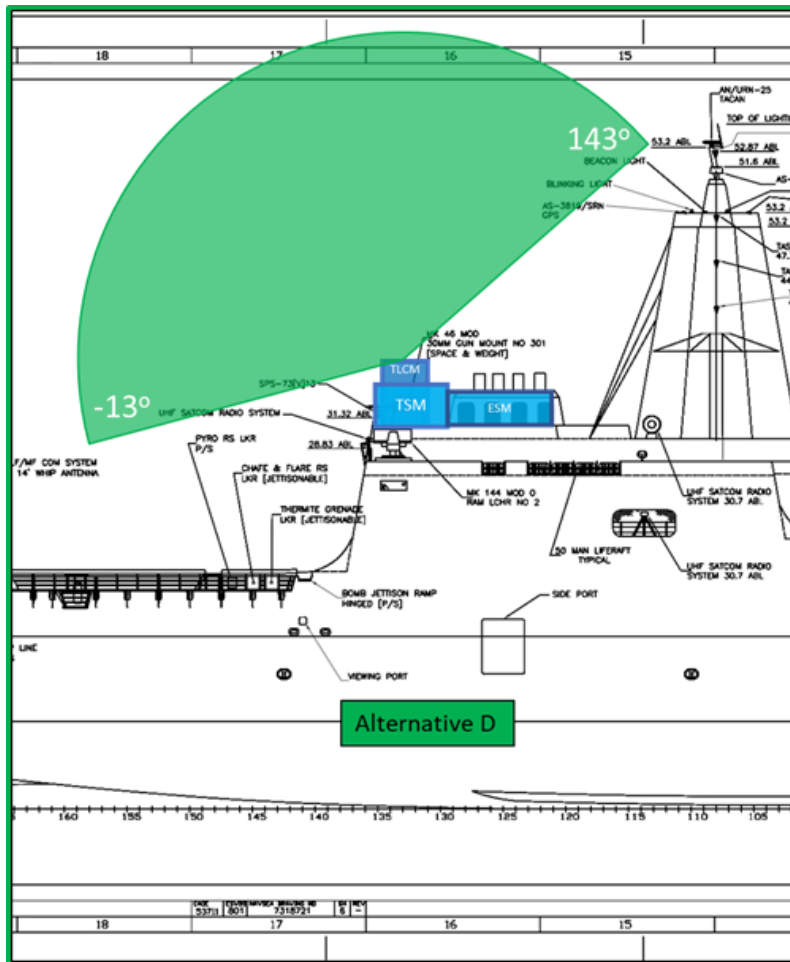


Figure 20. HEL Alternative D—Elevation Coverage

## 5. Alternative AC

Alternative AC combined alternatives A and C to provide two independent HEL systems for self-defense. The forward HEL used the ship's bow, 000°R, as the starting reference point. The total azimuth coverage was 230°, which ranged from 250°R to 120°R. The total elevation coverage was 146°, and ranged from -8° to 138°. The elevation coverage measured along the laser's longitudinal axis from 8° below the horizon to zenith and continued aft another 48°. The aft HEL used the stern of the ship, 180°R, as the starting reference point for azimuth coverage. The total azimuth coverage was 250°, which ranged from 030°R to 280°R. The total elevation coverage was 151°, and ranged from -12° to 139°. The elevation coverage measured along the laser's longitudinal axis from 12° below the

horizon to zenith and continued forward another  $49^\circ$ . Figures 21 and 22 depict the complete coverage provided by this alternative in azimuth and elevation, respectively.

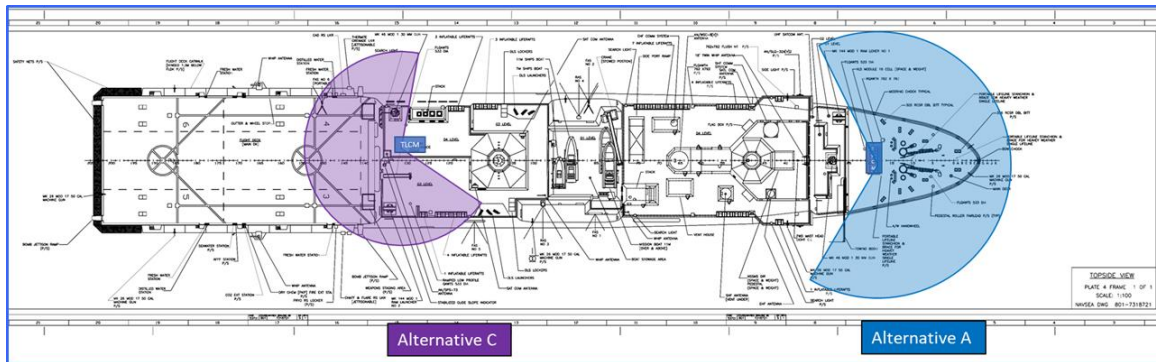


Figure 21. HEL Alternative AC—Azimuth Coverage

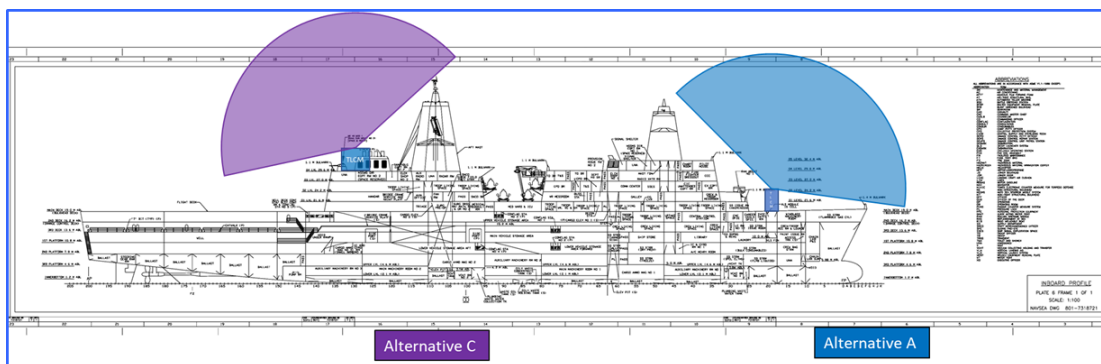


Figure 22. HEL Alternative AC—Elevation Coverage

## 6. Alternative AD

Alternative AD combined alternatives A and D to provide two independent HEL systems for self-defense. The forward HEL used the ship's bow,  $000^\circ\text{R}$ , as the starting reference point. The total azimuth coverage was  $230^\circ$ , which ranged from  $250^\circ\text{R}$  to  $120^\circ\text{R}$ . The total elevation coverage was  $146^\circ$ , and ranged from  $-8^\circ$  to  $138^\circ$ . The elevation coverage measured along the laser's longitudinal axis from  $8^\circ$  below the horizon to zenith and continued aft another  $48^\circ$ . The aft HEL used the stern of the ship,  $180^\circ\text{R}$ , as the starting reference point for azimuth coverage. The total azimuth coverage was  $270^\circ$ , which ranged from  $045^\circ\text{R}$  to  $315^\circ\text{R}$ . The total elevation coverage was  $156^\circ$ , and ranged from  $-13^\circ$  to  $143^\circ$ .

The elevation coverage measured along the laser's longitudinal axis from 13° below the horizon to zenith and continued forward another 53°. Figures 23 and 24 depict the complete coverage provided by this alternative in azimuth and elevation, respectively.

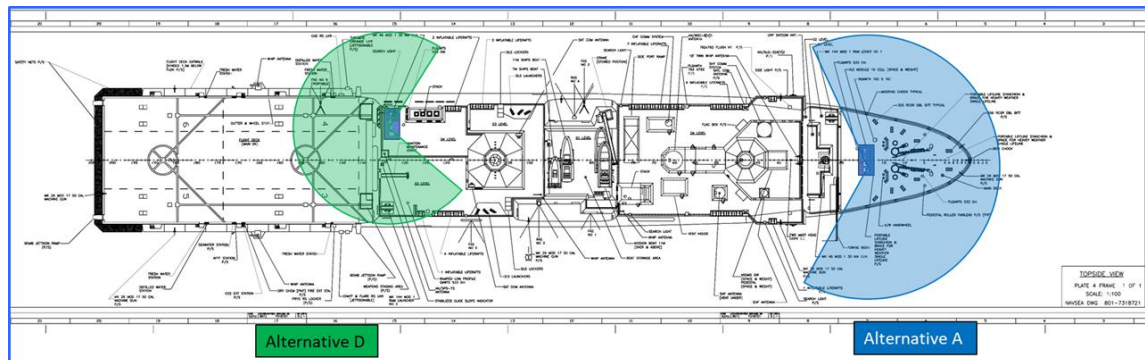


Figure 23. Alternative AD—Azimuth Coverage

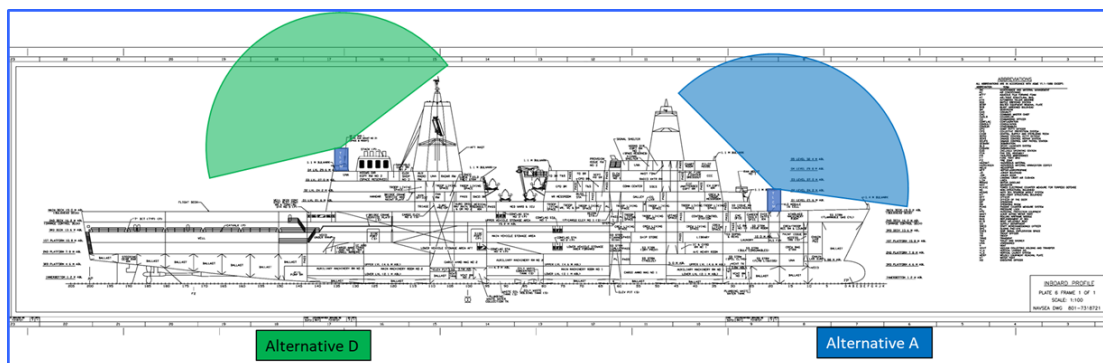


Figure 24. Alternative AD—Elevation Coverage

## 7. Alternative BC

Alternative BC combined alternatives B and C to provide two independent HEL systems for self-defense. The forward HEL used the ship's bow, 000°R, as the starting reference point. The total azimuth coverage was 245°, which ranged from 225°R to 110°R. The total elevation coverage was 157°, and ranged from -22° to 135°. The elevation coverage measured along the laser's longitudinal axis from 22° below the horizon to zenith and continued aft another 45°. The aft HEL used the stern of the ship, 180°R, as the starting reference point for azimuth coverage. The total azimuth coverage was 250°, which ranged

from 030°R to 280°R. The total elevation coverage was 151°, and ranged from -12° to 139°. The elevation coverage measured along the laser's longitudinal axis from 12° below the horizon to zenith and continued forward another 49°. Figures 25 and 26 depict the complete coverage provided by this alternative in azimuth and elevation, respectively.

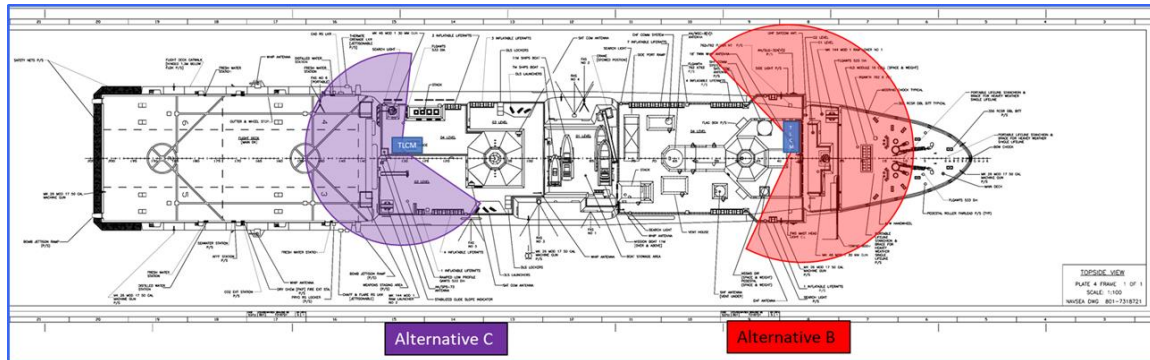


Figure 25. Alternative BC—Azimuth Coverage

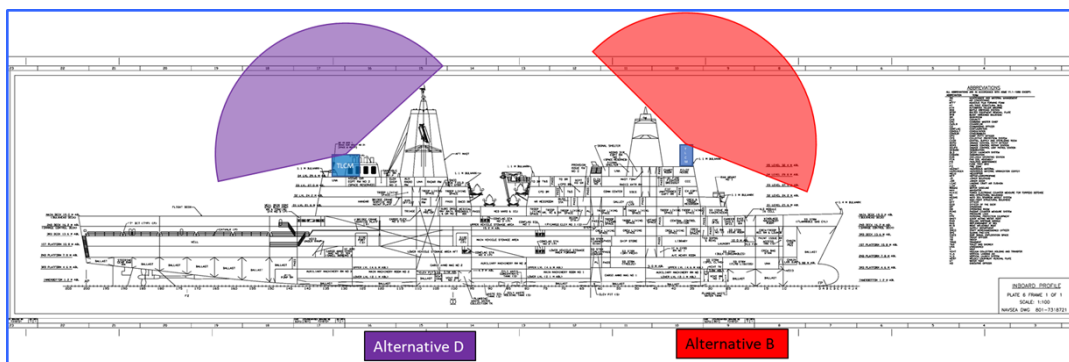


Figure 26. Alternative BC—Elevation Coverage

## 8. Alternative BD

Alternative BD combined alternatives B and D to provide two independent HEL systems for self-defense. The forward HEL used the ships bow, 000°R, as the starting reference point. The total azimuth coverage was 245°, which ranged from 225°R to 110°R. The total elevation coverage was 157°, and ranged from -22° to 135°. The elevation coverage measured along the laser's longitudinal axis from 22° below the horizon to zenith and continued aft another 45°. The aft HEL used the stern of the ship, 180°R, as the starting

reference point for azimuth coverage. The total azimuth coverage was  $270^{\circ}$ , which ranged from  $045^{\circ}\text{R}$  to  $315^{\circ}\text{R}$ . The total elevation coverage was  $156^{\circ}$ , and ranged from  $-13^{\circ}$  to  $143^{\circ}$ . The elevation coverage measured along the laser's longitudinal axis from  $13^{\circ}$  below the horizon to zenith and continuing forward another  $53^{\circ}$ . Figures 27 and 28 depict the complete coverage provided by this alternative in azimuth and elevation, respectively.

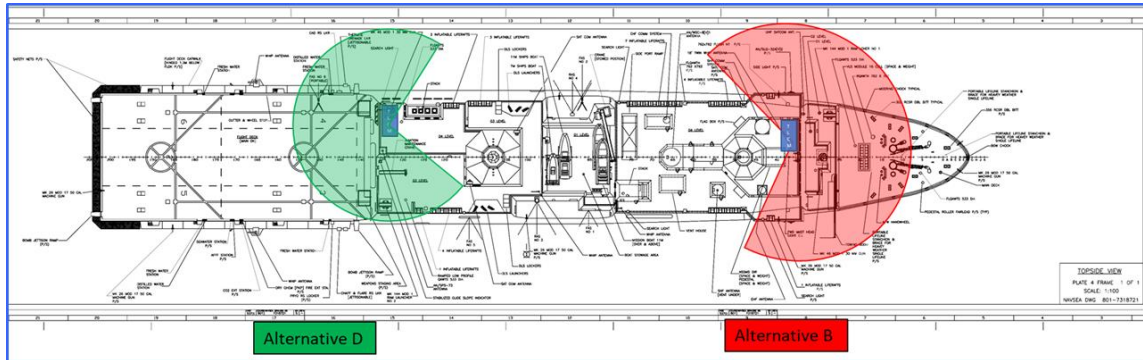


Figure 27. Alternative BD—Azimuth Coverage

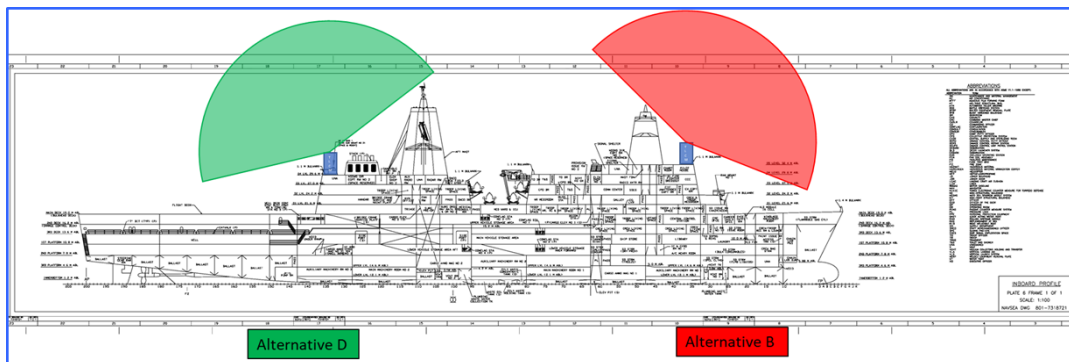


Figure 28. Alternative BD—Elevation Coverage

Identifying the alternative placements allowed for the visualization of the HEL components. The single alternatives are complementary to current defensive capabilities. The dual alternatives are not only complementary to current defensive capabilities, but they also offer expanded coverage. The placement of the HEL and its components are a necessary step in the SE process and the development of the integration concept. With the locations identified, determining how the HEL will incorporate with the LPD 17 is next.

### **C. INTEGRATION CONCEPT**

Development of the integration concept for a HEL system began with the completed concept architecture. The foundation of the integration concept primarily consisted of HEL placement selection, the various impacts of that decision, and definition of the evaluation method. This decision was dependent upon a process flow whereby an evaluation of alternatives provided ranked results, which included effects of both placement and integration consideration, where applicable.

Each alternative was evaluated and ranked against a set of criteria to determine the best placement for meeting the mission needs. The establishment of the evaluation criteria was meant to be clear and unambiguous, measurable, and relative to the program requirements (AcqNotes 2017). For continuity and traceability, the evaluation criteria aligned with program requirements. The numbering system for each list provided the link between the two, (i.e. R21 and C21). For a full-scale integration program, the team would evaluate each requirement and criteria against every alternative. For the purposes of this project, the focus was on the placement alternatives identified previously. The evaluation of each alternative followed a process. This combination of steps and integration considerations may prove helpful for future integration projects.

The team found five of the 22 identified evaluation criteria to be valid and applicable for the evaluation of alternatives. The remaining 17 unused evaluation criteria were still valuable in that they reflected useful thought processes, critical thinking, and should not be cast away. These evaluation criteria are in the appendix.

The five evaluation criteria are shipboard operations, turbulence, environment, azimuth coverage and elevation coverage. To evaluate each alternative against impacts from shipboard operations, an analysis of the scaled ship drawings captured the distance between the HEL and the LPD 17 system/activity causing the impact. For turbulence, on sunny days, the deck and bulkheads are much hotter than the ambient air. Solar heating of ship and airflow around ship's superstructure induces optical turbulence, which can potentially be worse than the turbulence experienced over water (Blau et al. 2018). The team analyzed the laser beam's distance traveled over the LPD 17 deck using the scaled

ship drawings and was useful in minimizing the turbulence effect on the laser's performance. For the HEL environment, one of the major considerations in terms of placement was proximity to the LPD 17 exhaust stacks, which emit hot gases of varying opacity. Negative impact on laser performance increases with the opacity of the hot gases. The HEL can avoid degraded performance by not shooting through the gases, thus increased distance from the stacks is desirable. For each alternative, the team measured the distance between the TLCM and the ship's stacks by analyzing the scaled ship drawings. Each alternative required a two-part evaluation for both azimuth and elevation coverage. The first was determining whether they met the requirement. The second was to sum the degrees covered. For azimuth coverage, those that met the requirement were ranked by their total azimuth coverage provided. Likewise, for elevation coverage, those that met the requirement were ranked by their total elevation coverage provided. A summary of the five evaluation criteria and their measurement methods are in Table 4.

Table 4. HEL Alternatives Evaluation Criteria

| Number | Criteria                                   | Evaluation method                         |
|--------|--------------------------------------------|-------------------------------------------|
| C09    | Effects of shipboard operations (minimize) | Distance between TLCM and ship's systems  |
| C10    | Turbulence (minimize)                      | Distance laser beam must travel over deck |
| C11    | Environment effects (minimize)             | Distance between TLCM and exhaust stacks  |
| C21    | Coverage - azimuth (maximize)              | Degree range                              |
| C22    | Coverage - elevation (maximize)            | Degree range                              |

First, each alternative needed to have a defined set of evaluation criteria. Then the creation of a process for performing the evaluation was next. The team decided that the creation of a Pugh matrix for this process was ideal because this method typically examines multiple alternatives and can grade an alternative negatively if an alternative does not meet the criterion. Values of -1, 0, or +1 are assigned to each alternative for each evaluation criterion; -1 if the alternative does not meet the criteria established, 0 if the alternative adequately meets the criterion, and +1 if the alternative meets and exceeds the criterion.

In the Pugh matrix evaluation of alternatives, the alternatives are compared to the baseline, usually the requirements. In this analysis, alternatives A through D were created with the bounds that azimuthal and elevation coverage were met, with all other alternatives falling out. In the beginning of the analysis of these evaluation criteria, it was realized that using the baseline for the Pugh matrix did not distinguish between better or worse alternatives, since all options met the requirement. There would be an opportunity for alternatives to receive either a 0 or 1, depending on if the measurements met or exceeded the requirement. Even in this case, all alternatives met 50% more than the requirement for elevation coverage, so all options would have received a score of 1 if the baseline Pugh matrix method was used. However, the Pugh matrix was partly chosen because of its ability to negatively score an alternative. For these reasons, the logic of evaluating criteria needed to be modified. Instead of grading each alternative against a baseline requirement, they were graded against each other. For each criterion, each alternative was ranked from 1 to 8; 1 as the best and 8 as the worst. After the rank was applied, the Pugh score of -1, 0 or -1 needed to be applied. To do this, a normal distribution was utilized, and ranks 1–2 received the 1 score, ranks 3–6 received the 0 score, and ranks 7–8 received the -1 score.

Table 5 helps to visualize this step with alternatives A and B assigned example unweighted, normally distributed, Pugh scores in italics.

Table 5. HEL Evaluation Matrix *with examples*

|    | Shipboard<br>operations<br>C09 | Turbulence<br>C10 | Environment<br>C11 | Azimuthal<br>coverage<br>C21 | Elevation<br>coverage<br>C22 |
|----|--------------------------------|-------------------|--------------------|------------------------------|------------------------------|
| A  | -1                             | -1                |                    |                              |                              |
| B  | -1                             | 0                 |                    |                              |                              |
| C  | 0                              | 0                 |                    |                              |                              |
| D  | 0                              | -1                |                    |                              |                              |
| AC | 0                              | 1                 |                    |                              |                              |
| AD | 0                              | 0                 |                    |                              |                              |
| BC | 1                              | 0                 |                    |                              |                              |
| BD | 1                              | 1                 |                    |                              |                              |

It was critical to determine the importance of the five criteria. Each criterion has a weighted value assigned. Each criterion's weight must sum to 1.0. The allocation of weighted values was important because it differentiated between multiple criteria and the influence of one over the other. The higher a criterion's value, the greater its significance. Weighted values would not apply if each criterion were equally important.

For this evaluation, the criteria C21 and C22 were deemed the most important to mission success due to the direct relationship they have to the ability to defend against incoming threats and their relationship to requirements R21 and R22. Requirement R21 reads, "The integrated HEL shall be capable of providing azimuthal coverage of 360° relative for two mounts or greater than 180° relative for a single mount." Requirement R22 reads, "The integrated HEL shall be capable of providing -5° to 90° coverage in elevation." If one alternative better addresses these requirements, it will receive a greater value, making it more likely the alternative to receive the best/highest score.

The total weight chosen for the two "coverage" criteria is 0.50. The 0.50 remaining total was divided across the turbulence, environment, and shipboard operations criteria. Turbulence, the next most important factor, received a weight of 0.20. This was because turbulence presented the risk of failure in attacking the target due to early distortion causing

large enough refraction when over the ship that the target, a km or further away, is missed (Blau et al. 2018). Environment and shipboard operations each received weights of 0.15 because each is limited by project scope to measurements of proximity between the TLCM and specific shipboard systems to depict laser degrading effects rather than more specific and lengthy performance studies. Again, the sum of all five weights added up to 1.00. All five of the criterion are important, but weighting assured that consideration to the priority of the requirements occurred. To continue the example from Table 5, the unweighted, normally distributed, Pugh scores in italics have had the weighting factors applied in Table 6. From this example, it was clear to see that while the Pugh matrix scores only allow for -1, 0 or 1, the importance of each criterion was important in the outcome. The example total for alternative A was -0.10, while the example score for alternative B was 0.35. In this example, alternative B was the better choice.

Table 6. Weighted Pugh Matrix *with examples*

|        | Shipboard<br>operations<br>C09 | Turbulence<br>C10 | Environment<br>C11 | Azimuthal<br>coverage<br>C21 | Elevation<br>coverage<br>C22 | Totals |
|--------|--------------------------------|-------------------|--------------------|------------------------------|------------------------------|--------|
| Weight | 0.15                           | 0.20              | 0.15               | 0.25                         | 0.25                         | 1.0    |
| A      | <i>-0.15</i>                   | <i>-0.20</i>      |                    |                              |                              |        |
| B      | <i>-0.15</i>                   | <i>0</i>          |                    |                              |                              |        |
| C      | <i>0</i>                       | <i>0</i>          |                    |                              |                              |        |
| D      | <i>0</i>                       | <i>-0.20</i>      |                    |                              |                              |        |
| AC     | <i>0</i>                       | <i>0.20</i>       |                    |                              |                              |        |
| AD     | <i>0</i>                       | <i>0</i>          |                    |                              |                              |        |
| BC     | <i>0.15</i>                    | <i>0</i>          |                    |                              |                              |        |
| BD     | <i>0.15</i>                    | <i>0.20</i>       |                    |                              |                              |        |

The weight factor assigned to each criterion was applied to the Pugh score of each alternative to arrive at the weighted Pugh score in Table 6. Then, the five values for each alternative are summed giving each alternative a total score across all evaluation criteria. Based on the highest total score, a final rank can be assigned to each alternative.

#### **D. SUMMARY**

In summary, the steps for the development of the integration concept have been presented in this chapter. These steps included developing the functional and physical decompositions or hierarchies, developing the concept architecture, and developing the integration concept. The HEL weapons system physical decomposition categorized the integration between the HEL and the LPD 17 class ship. The functional decomposition of the LPD and HEL distinguished the key differences between functions of both the HEL and the SSDS MK II. To visualize the concept architecture, the scaled ship drawings were used to depict alternative topside placement options for the TLCM. Integration concept development required assessment of system impacts in terms of compatibility and interoperability within the integrated system. The evaluation of alternatives approach created during this effort was performed during integration concept analysis.

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## IV. CONCEPT ANALYSIS AND DELIVERY

The integration concept developed in the previous phase included a complete set of placement alternatives and a framework for evaluating the alternatives using a Pugh matrix. The Pugh matrix provided a ranked list of the alternatives. Final analysis required examination of the ranking values against applicable integration considerations to arrive at a recommendation for the best placement alternative. The final recommendation included rationale accounting for the influence of various integration considerations. Figure 29 illustrates the final phase of the SE process, concept analysis and delivery.

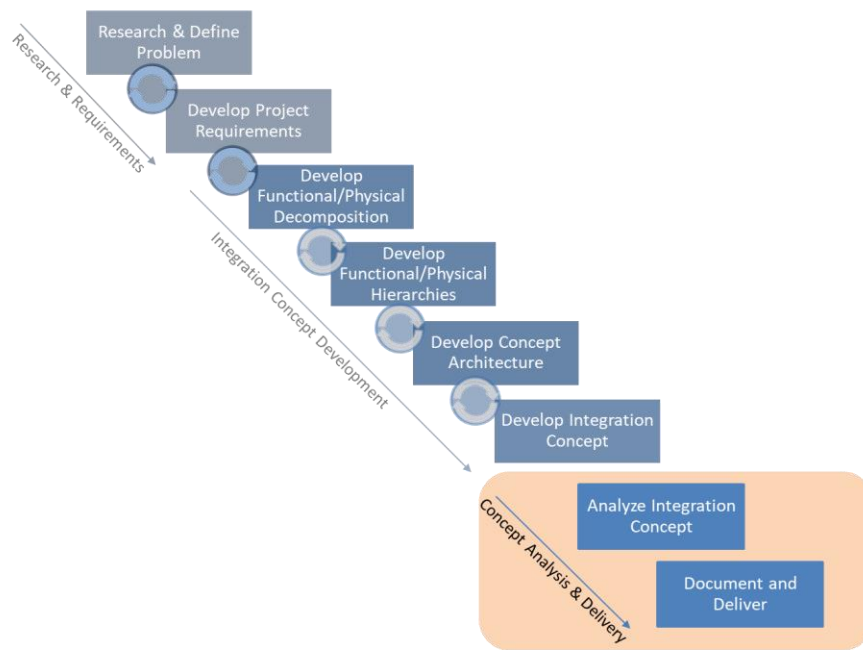


Figure 29. Concept Analysis and Delivery Phase

### A. ANALYZE INTEGRATION CONCEPT

Following the development of the integration concept, there existed a full set of placement alternative drawings, a subset of evaluation criteria found to be applicable and generally, within scope, plus an evaluation process that utilized a modified Pugh matrix

method. The analyze integration concept phase called for obtaining measures to populate the supporting Pugh matrix tables for evaluation of each of the five criteria: shipboard operations (C09), turbulence (C10), environment (C11), azimuthal coverage (C21), and elevation coverage (C22). These measures were collected and tables populated with a completed Pugh matrix that provided a ranking of the eight alternatives.

### **1. Shipboard Operations Criterion (C09)**

Shipboard operations were the first evaluation criteria and required two measurements. The distance between each TLMCM and the nearest 30 mm gun mount, and the distance between each TLMCM and the nearest RAM launcher. These measurements were important because the TLMCM's proximity to either shipboard weapon could have a negative impact on the HEL's performance. A possible negative impact is the introduction of jitter disturbance. There are two types of jitter: narrowband and broadband. Summarized from Yoon, Bateman, and Agrawal (2011), narrowband jitter is caused by mechanical vibrations and broadband is caused by atmospheric turbulence (Yoon, Bateman, and Agrawal 2011). The proximity of an operating 30 mm gun and/or RAM launcher to the TLMCM might cause mechanical vibrations. The temporary occlusion from the RAM launcher's exhaust may cause propagation loss to the HEL's beam. Either of these jitter disturbances are negative to the HEL because it can cause the beam to wander. A wandering beam does not allow the energy to focus on its target, which will increase the time for the laser to destroy a target. The specific impacts require further investigation in future studies. Figure 30 provides a birds-eye view of the distance between each individual alternative and the nearest 30 mm gun. Absent was alternative D because its position was in the placement of the 30 mm gun, so that distance was not applicable.

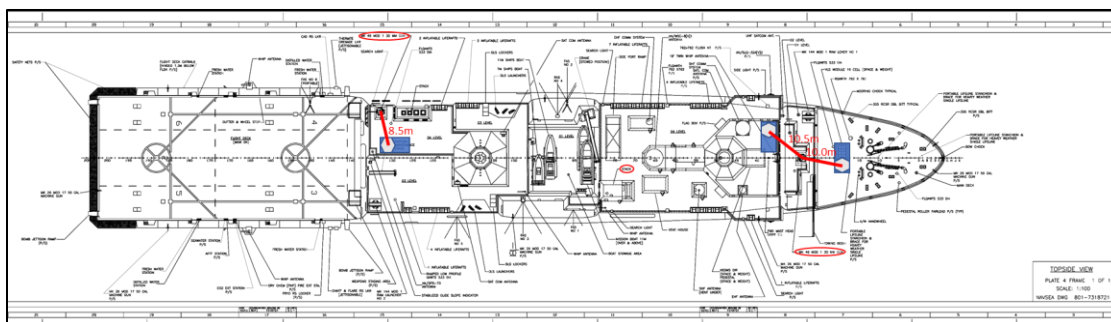


Figure 30. Top-down View—Measured Distance to Nearest 30 mm Gun

Figure 31 shows the distance between the forward 30 mm gun mount and alternatives A and B. The distance between alternative A and the 30 mm gun mount is 10.0 m. The distance between alternative B and the 30 mm gun mount is 10.5 m. These measurements were used to populate data for evaluation of the shipboard operations criterion, C09.

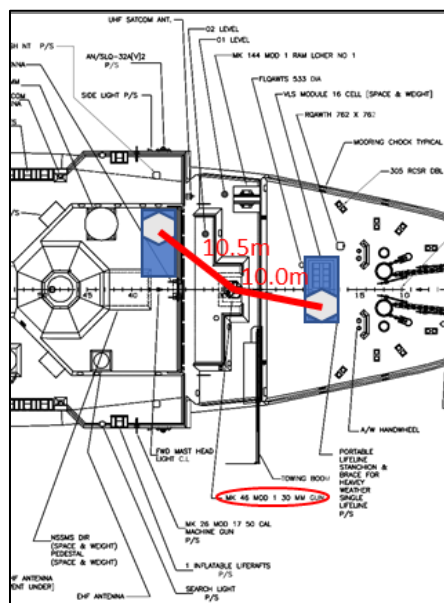


Figure 31. Top-down View Alternatives A and B Distance to Nearest 30 mm Gun

Figure 32 shows the distance between the aft 30 mm gun mount and alternative C. The distance between alternative C and the 30 mm gun mount is 8.5 m. The distance for

alternative D was not applicable since its placement was in the same location and replaced the aft gun mount. These measurements were used to populate data for evaluation of the shipboard operations criterion, C09.

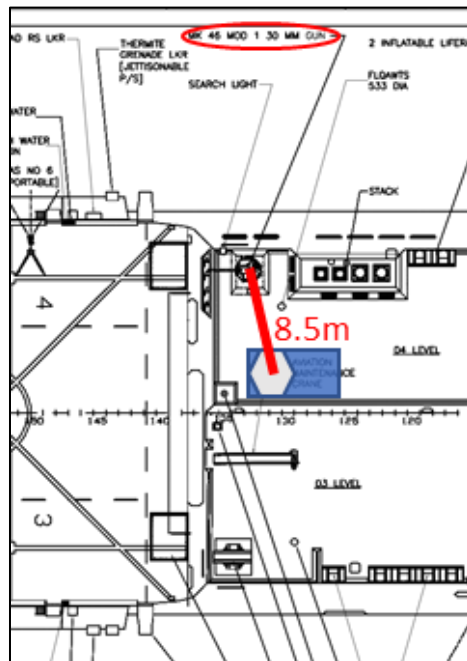


Figure 32. Alternative C Measurement to Nearest 30 mm Gun

Table 7 is the distance between each alternative and the nearest 30 mm gun. The distances for each dual alternative takes the average of the two individual placements. Averaging the two measures was decided as the most straightforward approach to evaluate the single and dual alternatives against each another. Then each alternative was ranked from best to worst based on its distance from farthest to closest. Since alternative D replaced the aft 30 mm gun, an N/A was applied for both its individual placement and the dual alternatives. The greater distances were given a better ranking because this would minimize the potential for interference between the HEL and the 30 mm gun.



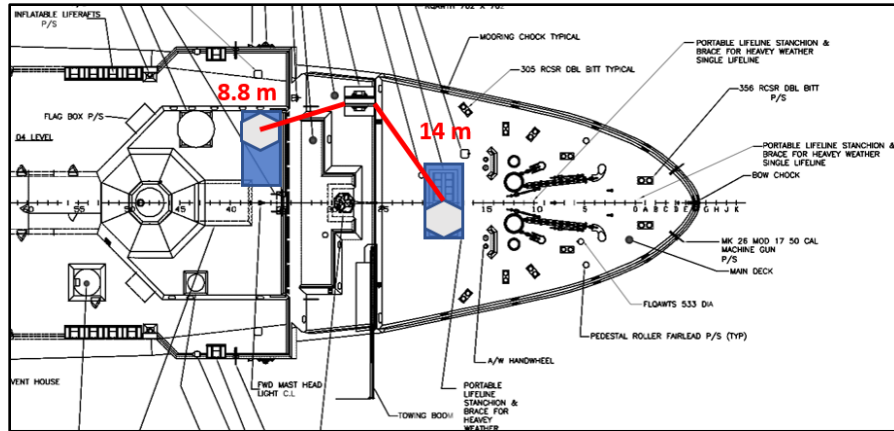


Figure 34. Top-down View Alternatives A and B Distance to Nearest RAM Launcher

Figure 35 shows the distance between the aft RAM launcher and alternative C. The distance between alternative C and the RAM launcher was 14.9 m. The distance between alternative D and the RAM launcher was 21.5 m. These measurements were used to populate data for evaluation of the shipboard operations criterion, C09.

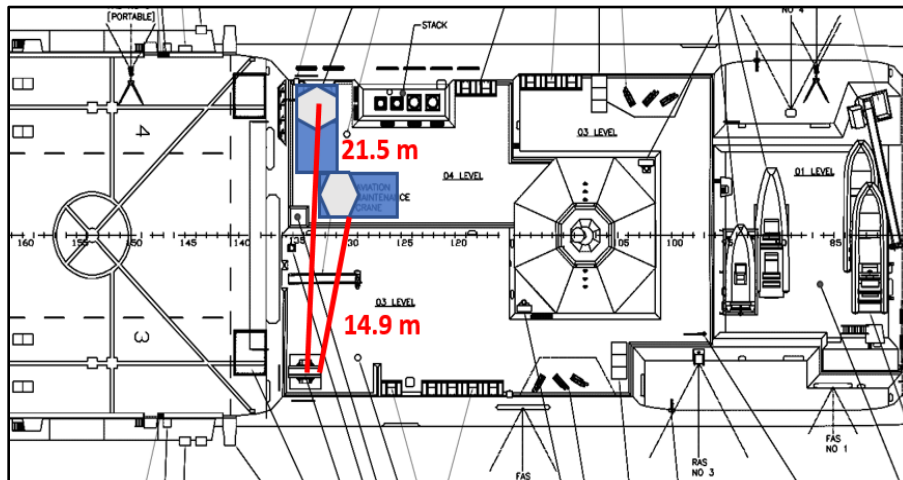


Figure 35. Top-down View Alternatives C and D Distance to Nearest RAM Launcher

Similar to Table 7, Table 8 shows the distance between each alternative and the nearest RAM launcher. The distances for each dual alternative takes the average of the two individual placements; then each alternative was given a ranking from best to worst based

on its distance from farthest to closest. The greater distances were given a better ranking because typically, this would minimize the potential for interference between the HEL and the RAM launcher.

Table 8. Shipboard Operations (distance to nearest RAM launcher)

|      | Shipboard operations (RAM being launched) |      |
|------|-------------------------------------------|------|
| Alt. | Distance to nearest RAM launcher (m)      | Rank |
| A    | 14                                        | 6    |
| B    | 8.8                                       | 8    |
| C    | 14.9                                      | 4    |
| D    | 21.5                                      | 1    |
| AC   | 14, 14.9 (Avg 14.45)                      | 5    |
| AD   | 14, 21.5 ( Avg 17.75)                     | 2    |
| BC   | 8.8, 14.9 (Avg 11.85)                     | 7    |
| BD   | 8.8, 21.5 (Avg 15.15)                     | 3    |

The results showed that alternative D was the best option if only the distance was being considered; however, there is more to consider when analyzing the results. For example, alternative B had the lowest ranking due to its proximity to the forward RAM launcher but may not be the worst position due to the location of alternative B. Alternative B was positioned above the bridge, which is at least two deck levels above the RAM launcher. This height difference should minimize the shock factors from launching a missile; however, the immense heat and smoke plume that results from the missile launch could interfere with the HEL if a coordinated engagement is required. Alternative C showed similar results with the RAM launcher being located in close proximity; however, it is an entire deck level below alternative C's position. These details can be utilized to solidify the alternative analysis and must be considered to ensure the best alternative is recommended.

The rankings from the 30 mm gun (Table 7) and RAM launcher (Table 8) were then summed to form a single representation, Table 9, for the impacts of both systems upon each alternative. The sums were then used to create new rankings for the alternatives. The shipboard operations rankings were then given a Pugh score that normally distributed the alternatives to distinguish between the alternatives from best to worst.

Table 9. Shipboard Operations (combined sum with Pugh score)

|      | Shipboard operations (30mm gun firing and RAM being launched) |            |            |            |
|------|---------------------------------------------------------------|------------|------------|------------|
| Alt. | Rank<br>(30 mm Gun)                                           | Rank (RAM) | SUM (Rank) | Pugh score |
| A    | 3                                                             | 6          | 9 (4)      | 0          |
| B    | 1                                                             | 8          | 9 (5)      | 0          |
| C    | 7                                                             | 4          | 11 (7)     | -1         |
| D    | -                                                             | 1          | 1 (1)      | 1          |
| AC   | 6                                                             | 5          | 11 (6)     | 0          |
| AD   | 3                                                             | 2          | 5 (3)      | 0          |
| BC   | 5                                                             | 7          | 12 (8)     | -1         |
| BD   | 1                                                             | 3          | 4 (2)      | 1          |

## 2. Turbulence Criterion (C10)

In evaluating the turbulence criterion, the distance was measured from the TLCDM to the deck edge for alternatives A–D (Figure 36) and combined using an average of these for alternatives AC–BD.

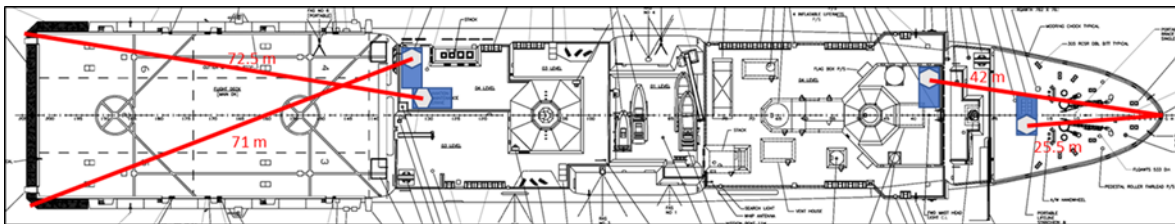


Figure 36. Alternatives A-D Maximum Distance to Deck Edge

Understanding that turbulence is viewed here as the primary result of the laser traveling through air columns subject to heating differentials. Heating differentials are the difference between cooler ambient air and the air heated by the ship's decks. For this reason, the primary measure was intended to capture the maximum distance the laser could travel from each alternative's placement across the hot decks. The simplified approach scores the alternative with the maximum distance as the worst one and with improving scores as the distance decreased. There are other impacts such as heat from exhaust stacks and heat from other ship structures that would also likely have an impact on turbulence, but calculating each factor precisely requires further study. Ultimately, understanding and representing the combined effects for all sources of turbulence requires mitigation through intelligent integration decisions beyond the scope of this work.

Figure 37 shows the maximum distance between alternative A and the deck edge. The maximum distance the laser can travel before crossing the deck edge is 25.5 meters. The measurement was used to populate data for evaluation of the turbulence criterion, C10.

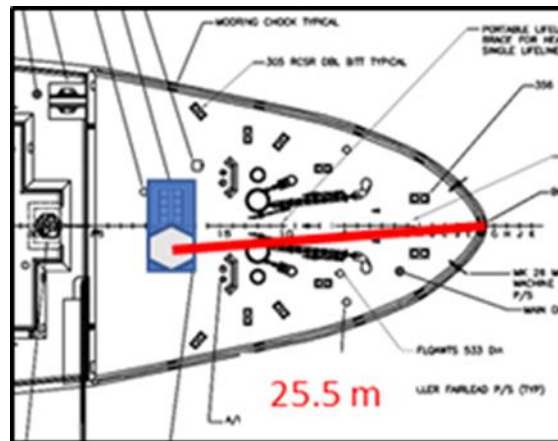


Figure 37. Alternative A Maximum Distance to Deck Edge 25.5 Meters

Figure 38 shows the maximum distance between alternative B and the deck edge. The maximum distance the laser can travel before crossing the deck edge is 42 meters. The measurement was used to populate data for evaluation of the turbulence criterion, C10.

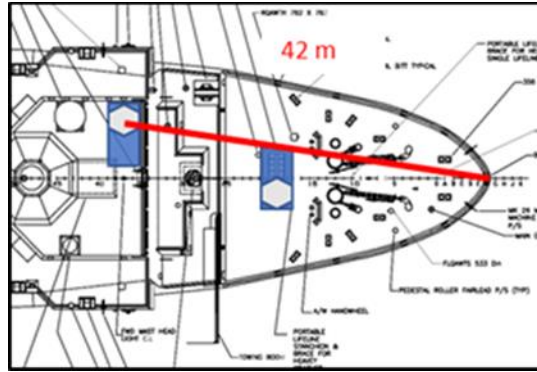


Figure 38. Alternative B Maximum Distance to Deck Edge 42 Meters

Figure 39 shows the maximum distance between alternative C and the deck edge. The maximum distance the laser can travel before crossing the deck edge is 72.5 meters. The measurement was used to populate data for evaluation of the turbulence criterion, C10.

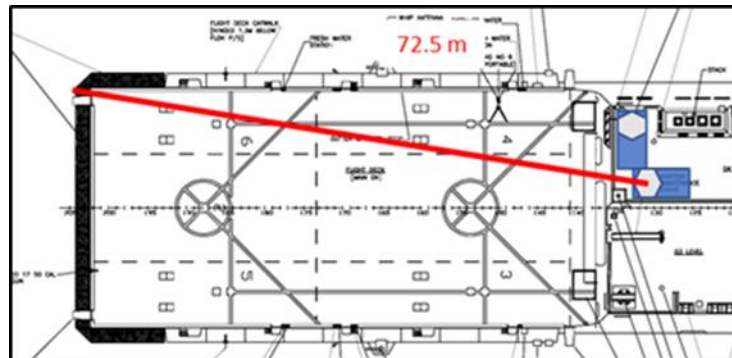


Figure 39. Alternative C Maximum Distance to Deck Edge 72.5 Meters

Figure 40 shows the maximum distance between alternative D and the deck edge. The maximum distance the laser can travel before crossing the deck edge is 71 meters. The measurement was used to populate data for evaluation of the turbulence criterion, C10.

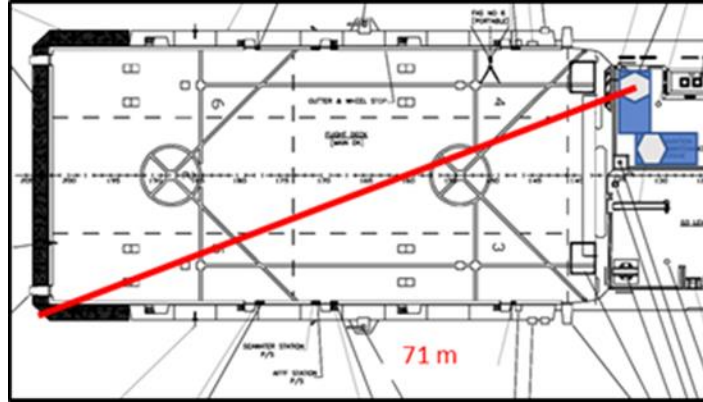


Figure 40. Alternative D Maximum Distance to Deck Edge 71 Meters

To summarize the drawing analysis provided, Table 10 compiles all of the maximum distances the HEL beam must travel over the deck. All alternatives were assigned a rank of 1 thru 8, 1 being the shortest maximum distance (best case) and 8 being the furthest maximum distance (worst case). The Pugh score was then applied in a normal distribution method.

Table 10. Turbulence (maximum distance over deck)

| Alt. | Turbulence                 |      |            |
|------|----------------------------|------|------------|
|      | Max distance over deck (m) | Rank | Pugh score |
| A    | 25.5                       | 1    | 1          |
| B    | 42                         | 2    | 1          |
| C    | 72.5                       | 8    | -1         |
| D    | 71                         | 7    | -1         |
| AC   | 25.5, 71 (Avg 48.25)       | 3    | 0          |
| AD   | 25.5, 72.5 (Avg 49)        | 4    | 0          |
| BC   | 42, 71 (Avg 56.5)          | 5    | 0          |
| BD   | 42, 72.5 (Avg 57.25)       | 6    | 0          |

While the exhaust stacks emit hot gases that cause turbulence for a laser passing near or through them, the more significant effects of the emissions are particulates. The

opacity of the gas may prevent laser transmission by absorbing significantly more power, causing the laser performance to degrade more absolutely than the brief turbulence created. For this reason, the exhaust stacks' effects were captured for evaluation under the environment C11 criterion.

### 3. Environment Criterion (C11)

In evaluating the environment criterion, the distance was measured from the TLCM to the nearest exhaust stack for alternatives A–D (Figure 41) and combined using an average of these for alternatives AC–BD.

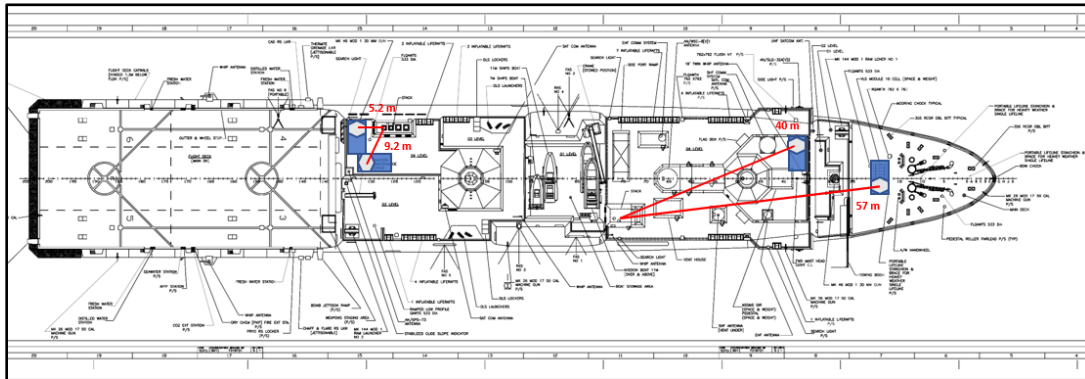


Figure 41. Alternatives A-D Minimum Distance to Exhaust Stacks

Figure 42 shows the distance between the forward exhaust stacks and alternatives A and B. The distance between alternative A and the nearest exhaust stack was 57 m. The distance between alternative B and the nearest exhaust stack was 40 m. These measurements were used to populate data for evaluation of the shipboard environment criterion, C11.

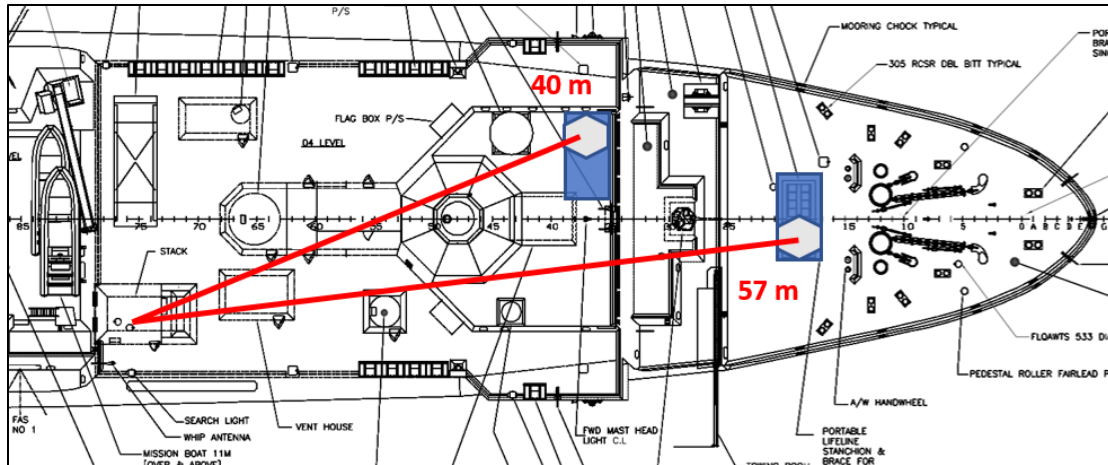


Figure 42. Alternatives A and B Minimum Distance to Forward Exhaust Stacks

Figure 43 shows the distance between the aft exhaust stacks and alternatives C and D. The distance between alternative C and the nearest exhaust stack was 9.2 m. The distance between alternative D and the nearest exhaust stack was 5.2 m. These measurements were used to populate data for evaluation of the shipboard environment criterion, C11.

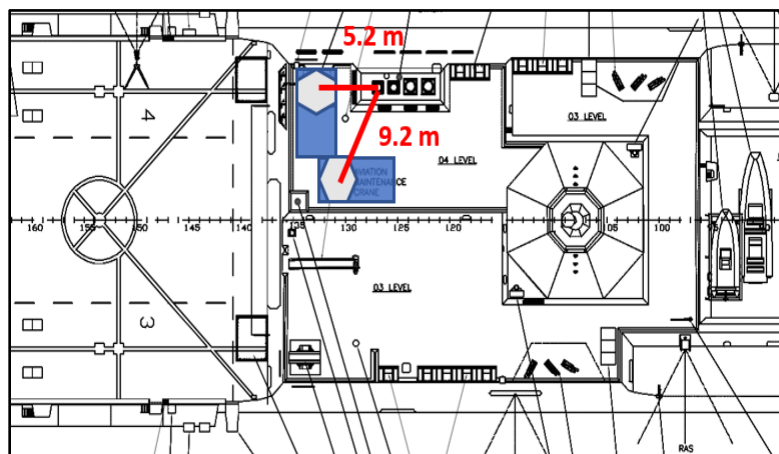


Figure 43. Alternatives C and D Minimum Distance to aft Exhaust Stacks

To summarize the drawing analysis provided earlier, Table 11 compiles all of the worst-case distances between the TLCM and the nearest exhaust stacks. All alternatives

were assigned a rank of 1 thru 8, 1 being the longest distance from the exhaust stacks and 8 being the shortest. The Pugh score was then applied in a normal distribution method.

Table 11. Environment Criterion (distance to nearest exhaust stacks)

| Alt. | Environment                            |      |            |
|------|----------------------------------------|------|------------|
|      | Distance to nearest exhaust stacks (m) | Rank | Pugh score |
| A    | 57                                     | 1    | 1          |
| B    | 40                                     | 2    | 1          |
| C    | 9.2                                    | 7    | -1         |
| D    | 5.2                                    | 8    | -1         |
| AC   | 57, 9.2 (Avg. 33.1)                    | 3    | 0          |
| AD   | 57, 5.2 (Avg. 31.1)                    | 4    | 0          |
| BC   | 40, 9.2 (Avg. 24.6)                    | 5    | 0          |
| BD   | 40, 5.2 (Avg. 22.6)                    | 6    | 0          |

The results from the analysis showed that the minimum distance to the exhaust stacks for alternatives A and B rank on top. This makes sense, as they are located the furthest away from exhaust stacks. Due to the large distance between the two and the exhaust trail leading aft when the ship is moving forward or due to relative winds, there will be little to no interference with stack gasses for the two forward HEL alternatives. Alternatives C and D, on the other hand, are located in close proximity to the aft exhaust stacks. With only 5.2 meters of separation between the HEL and exhaust stacks, and similar heights, alternative D is the lowest ranking option. The stack gasses expended from the aft stacks will most certainly interfere with the HEL operation, whether the ship is making way or not. With the rare exception of relative winds moving the exhaust toward the bow, this presents to potential issues during an engagement. With compressed timelines required of our advanced threats, this interference could lead to failed engagements and vulnerability of the ship and crew and is worth further investigation or detailed studies.

#### 4. Azimuthal Coverage Criterion (C21)

To summarize the analysis of scaled ship drawings provided in Chapter III, Table 12 compiles all of the degrees of azimuthal coverage. All alternatives are assigned a rank

of 1 thru 8, 1 being the largest total and 8 being the smallest. The Pugh score was then applied in a normal distribution method.

Table 12. Azimuthal Coverage Criterion

| Azimuthal coverage (maximize coverage) |                    |      |            |
|----------------------------------------|--------------------|------|------------|
| Alt.                                   | Coverage sector(s) | Rank | Pugh score |
| A                                      | 230°               | 8    | -1         |
| B                                      | 245°               | 7    | -1         |
| C                                      | 250°               | 5    | 0          |
| D                                      | 270°               | 6    | 0          |
| AC                                     | 230°, 250°         | 3    | 0          |
| AD                                     | 230°, 270°         | 1    | 1          |
| BC                                     | 245°, 250°         | 4    | 0          |
| BD                                     | 245°, 270°         | 2    | 1          |

The ranking of the azimuthal coverage shows the favored and the least favored HEL mount locations. All of the identified mount locations (or alternative placements) met the stakeholder's desired minimum requirements, 180° for a single mount and 360° for dual mounts. The two highest ranked mount alternatives were BD and AD and received a rank of 1 and 2, which translated into a Pugh score of +1. The two lowest ranked alternatives of 7 and 8 are mount locations A and B, which received a Pugh score of -1.

The dual mount coverage sectors listed in Table 12 are specific to each mount where the 360° requirement is specific to the ship. Figure 44 shows the coverage sectors for alternatives B and D expanded until they intersect the ship's coverage can be seen along with two gaps in coverage near the ship on each beam.

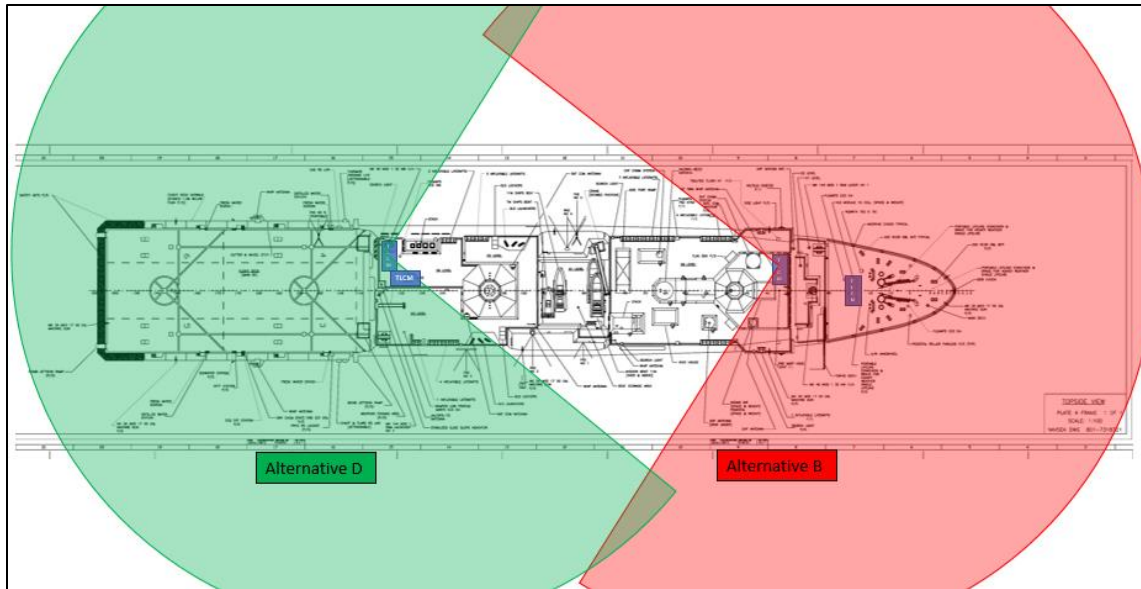


Figure 44. Alternative BD Coverage Envelope

## 5. Elevation Coverage Criterion (C22)

To summarize the drawing analysis provided in Chapter III, Table 13 compiles all of the degrees of elevation coverage. All alternatives are assigned a rank of 1 thru 8, 1 being the largest total and 8 being the smallest. The Pugh score was then applied in a normal distribution method.

Table 13. Elevation Coverage Criterion

| Alt. | Elevation coverage |      |            |
|------|--------------------|------|------------|
|      | Coverage sector(s) | Rank | Pugh score |
| A    | 146°               | 8    | -1         |
| B    | 157°               | 5    | 0          |
| C    | 151°               | 7    | -1         |
| D    | 156°               | 6    | 0          |
| AC   | 146°, 151°         | 4    | 0          |
| AD   | 146°, 156°         | 3    | 0          |
| BC   | 157°, 151°         | 2    | 1          |
| BD   | 157°, 156°         | 1    | 1          |

Ranking the elevation coverage showed the favored and the least favored HEL mount locations. All of the identified mount locations (or alternative placements) met the stakeholder's desired minimum requirements, -5° to 90° coverage in elevation. The two highest ranked mounts are alternatives BD and BC, which received a rank of 1 and 2 and translated into a Pugh score of +1. The two lowest ranked alternatives of 7 and 8 are mount locations A and C, which received a Pugh score of -1. The results of the ranking were documented and summarized with a recommendation.

Note that this assessment was based only upon visual representation and a generalized estimate of coverage along the fore and aft line of the ship. To discern the complete elevation coverage provided by an alternative, a detailed study must be undertaken that would confirm this coverage from 000° relative to 359° relative. One of the expected results from such a study might show that a single mount solution is not going to be capable of providing full elevation coverage all the way around the ship. For example, a forward mount is very likely to have a gap in its coverage for a low altitude ASCM coming from directly astern.

A summary table is provided in Table 14 with all measured data points discussed previously. The means of measurement and the unit of measure are provided for each criterion along with whether minimizing or maximizing the value is desirable. The measured values for each alternative are populated and ranking of these values will be used in determining the unweighted Pugh score used in the subsequent table.

Table 14. Summary Criterion Measures

|      | Shipboard Operations             |                                      | Turbulence                 | Environment                            | Azimuthal coverage | Elevation coverage |
|------|----------------------------------|--------------------------------------|----------------------------|----------------------------------------|--------------------|--------------------|
|      | Distance to nearest 30mm Gun (m) | Distance to nearest RAM launcher (m) | Max distance over deck (m) | Distance to nearest exhaust stacks (m) | Coverage sector(s) | Coverage sector(s) |
| Alt. | Maximize                         | Maximize                             | Minimize                   | Maximize                               | Maximize           | Maximize           |
| A    | 10.0                             | 14                                   | 25.5                       | 57                                     | 230°               | 146°               |
| B    | 10.5                             | 8.8                                  | 42                         | 40                                     | 245°               | 157°               |
| C    | 8.5                              | 14.9                                 | 72.5                       | 9.2                                    | 250°               | 151°               |
| D    | N/A                              | 21.5                                 | 71                         | 5.2                                    | 270°               | 156°               |
| AC   | 10.0, 8.5<br>(Avg. 9.25)         | 14, 14.9<br>(Avg. 14.45)             | 25.5, 71<br>(Avg. 48.25)   | 57, 9.2<br>(Avg. 33.1)                 | 230°, 250°         | 146°, 151°         |
| AD   | 10.0, N/A<br>(Avg. 10)           | 14, 21.5<br>(Avg. 17.75)             | 25.5, 72.5<br>(Avg. 49)    | 57, 5.2<br>(Avg. 31.1)                 | 230°, 270°         | 146°, 156°         |
| BC   | 10.5, 8.5<br>(Avg. 9.5)          | 8.8, 14.9<br>(Avg. 11.85)            | 42, 71<br>(Avg. 56.5)      | 40, 9.2<br>(Avg. 24.6)                 | 245°, 250°         | 157°, 151°         |
| BD   | 10.5, N/A<br>(Avg. 10.5)         | 8.8, 21.5<br>(Avg. 15.15)            | 42, 72.5<br>(Avg. 57.25)   | 40, 5.2<br>(Avg. 22.6)                 | 245°, 270°         | 157°, 156°         |

## B. DOCUMENT AND DELIVER

The completed lower level analysis results, as described previously, were used to populate the unweighted Pugh score summary, Table 15. The results were transferred into the columns indicated from Table 10 - Shipboard operations (combined sum with Pugh score), Table 10 - Turbulence (maximum distance over deck), Table 11 - Environment criterion (distance to nearest exhaust stacks), and Table 12 - Azimuthal coverage criterion, and Table 13 - Elevation coverage criterion, respectively.

Table 15. Unweighted Pugh Score Summary Table

| Alt. | Shipboard<br>operations<br>C09 | Turbulence<br>C10 | Environment<br>C11 | Azimuthal<br>coverage<br>C21 | Elevation<br>coverage<br>C22 |
|------|--------------------------------|-------------------|--------------------|------------------------------|------------------------------|
| A    | 0                              | 1                 | 1                  | -1                           | -1                           |
| B    | 0                              | 1                 | 1                  | -1                           | 0                            |
| C    | -1                             | -1                | -1                 | 0                            | -1                           |
| D    | 1                              | -1                | -1                 | 0                            | 0                            |
| AC   | 0                              | 0                 | 0                  | 0                            | 0                            |
| AD   | 0                              | 0                 | 0                  | 1                            | 0                            |
| BC   | -1                             | 0                 | 0                  | 0                            | 1                            |
| BD   | 1                              | 0                 | 0                  | 1                            | 1                            |

The unweighted scores were transferred and multiplied by the columnar weight to Table 16 resulting in a set of individually weighted Pugh scores for each criterion. Each row was summed to arrive at the final Pugh scores for the respective alternatives.

Table 16. Pugh Matrix

|        | Shipboard<br>operations<br>C09 | Turbulence<br>C10 | Environment<br>C11 | Azimuthal<br>coverage<br>C21 | Elevation<br>coverage<br>C22 | Totals |
|--------|--------------------------------|-------------------|--------------------|------------------------------|------------------------------|--------|
| Weight | 0.15                           | 0.20              | 0.15               | 0.25                         | 0.25                         | 1.0    |
| A      | 0                              | 0.20              | 0.15               | -0.25                        | -0.25                        | -0.15  |
| B      | 0                              | 0.20              | 0.15               | -0.25                        | 0                            | 0.10   |
| C      | -0.15                          | -0.20             | -0.15              | 0                            | -0.25                        | -0.75  |
| D      | 0.15                           | -0.20             | -0.15              | 0                            | 0                            | -0.20  |
| AC     | 0                              | 0                 | 0                  | 0                            | 0                            | 0      |
| AD     | 0                              | 0                 | 0                  | 0.25                         | 0                            | 0.25   |
| BC     | -0.15                          | 0                 | 0                  | 0                            | 0.25                         | 0.10   |
| BD     | 0.15                           | 0                 | 0                  | 0.25                         | 0.25                         | 0.65   |

The results in Table 16 showed that the dual HEL mount alternative BD received the highest value and without further interpretation would imply that it best satisfied the requirements according to the evaluation criteria. There was sufficient influence from other factors that required interpretation before recommending an alternative for this integration. It was necessary to breakout each alternative separately and consider not only the Pugh

matrix results, but also take into account what was known, good and bad, about each one such that a comprehensive and clear understanding could be achieved.

## **1. Alternative A**

Alternative A received a final Pugh score of -0.15, which ranked 6<sup>th</sup> out of 8 alternatives. This alternative is positioned on the bow in the footprint reserved for the LPD 17 modification for VLS. It received four extreme results across the five criteria ranking best for the turbulence and environment criteria. Alternative A ranked worst for azimuthal coverage and elevation coverage criteria, resulting in its low rank overall since the weighted values were highest with both azimuthal and elevation coverage.

Alternative A is a viable option given the modification to the LPD 17 ship and all components that accompany it. There are numerous factors outside the general evaluation criteria that must be considered prior to selection. The design for the SSL-TM in this configuration ensures maximum portability in order to easily install the system, including the scaled support components for the TLMCM that fit within the structure of the VLS. The ability for the HEL to be essentially housed until required, increases the survivability of the system against not only wear and tear but more importantly the harsh elements out at sea.

There are negative effects that are possible from this alternative as well, especially given the system's placement near the forecastle. While conducting evolutions at restricted maneuvering, it is common practice to have 10–15 personnel on station. Causing the potential for a personnel hazard if HEL operations were required for any reason. Although it introduces personnel risk, this is not a new concept as current warships, such as destroyers and cruisers, have similar weapons systems that would force deck personnel to evacuate prior to an engagement. Although outside our project scope, further studies in the HEL operations and capabilities themselves could yield pivotal data in determining the best alternative including reliability analysis, availability, and maintainability of the system.

## **2. Alternative B**

Alternative B received a final Pugh score of 0.10, which tied for 3<sup>rd</sup> out of 8 alternatives with alternative BC. Alternative B is positioned to port above the pilothouse on the 05 level. It received three extreme results across the five criteria ranking second best for the turbulence and environment criteria and second worst for the azimuthal coverage criterion. Alternative B is the only alternative that scored a negative value within a coverage criterion and was able to maintain a positive value for its final score. The favorable scores in both turbulence and environment made up for the negative value in azimuthal coverage.

This alternative is a very suitable option for the HEL placement. The TLCM location above the pilothouse gives the weapon system an added intimidation factor as it towers above the bridge perfectly positioned for the threat. As seen in the results, the elevation coverage was significantly increased by positioning the TLCM higher on the ship. As with all alternatives, there are important factors that must be considered outside of the evaluation criteria. One of the unique designs of the LPD 17 class ship is there is not one straight (90°) piece of metal on the entire ship. If there is a component or section with exposed straight edges, a passive countermeasure system (PCMS), in the form of neoprene rubber tiles to minimize the radar cross section (RCS) of the ship, is applied. Minimizing RCS is a critical factor in the detectability and survivability of the ship. The HEL will need PCMS, as the supporting components are boxes and exposed topside. In addition, being placed above the pilothouse will require serious consideration in the physical wiring and cabling requested of the system. The current layout of the deck below alternative B's placement may not be suitable and warrants further study.

## **3. Alternative C**

Alternative C received a final Pugh score of -0.75, which ranked 8<sup>th</sup> out of 8 alternatives. Alternative C is positioned slightly to port of centerline just forward of the flight deck on the 04 level. This placement received four extreme results across the five criteria ranking second worst for the shipboard operations, turbulence, environment, and elevation coverage criteria. Alternative C is the only case to obtain all negatives scores that

were not zero, which accounts for its worse rank overall. Alternative C provides defensive coverage for the aft section of the ship.

The laser placement for this alternative provides less laser coverage than alternative D. The feasibility of using the laser from this placement poses a concern because flight operations occur at the aft section of the ship. Future coordination between representatives from the aviation and surface warfare communities must occur to develop standard operating procedures (SOPs) for laser use before, during, and after flight operations. The availability of multiple weapons systems operating at the same time and how this will occur needs to be addressed, also. Is it possible to operate more than one weapons system at once? Who will operate them? Procedures need to be established if this is desired. The external placement of all HEL components and its open exposure to the starboard side may change the ship's radar signature. The ship's vulnerability and radar signature will need further analysis to determine if this placement is suitable.

#### **4. Alternative D**

Alternative D received a final Pugh score of -0.20, which ranked 7<sup>th</sup> out of 8 alternatives. The alternative is positioned to port just forward of the flight deck on the 04 level and displaces the existing aft 30 mm gun mount. Alternative D received three extreme results across the five criteria ranking best for the shipboard operations criterion with a disclaimer and worst for both the turbulence and environment criteria. The disclaimer for the shipboard operations ranking was because of alternative D's distance to the 30 mm gun mount. The measurement was deemed not applicable since this alternative's placement displaced the aft 30 mm gun mount. The decision resulted in a non-ranking result and when summed with the RAM launcher's ranking, alternative D's overall shipboard ranking assumed the value of the latter. While alternative D was nominal in terms of azimuthal and elevation coverage, the other three criteria were summed to a negative overall score.

Future studies into the compatibility should occur, to determine if the alternative could utilize any of the existing electrical and physical hardware such as wiring harnesses and framing. The maintainability may pose issues due to its position directly behind the ship's exhaust stacks. The position of this alternative may inhibit a maintainer's ability to

perform a proper boresight for the laser, which will result in an unsuccessful calibration. The degradability into losing an existing weapons system with the 30 mm gun needs analysis to determine if the placement is worth the trade. The initial evaluation of alternative D's placement looks to minimize any changes to the ship's radar cross-section, since the components appear to blend into the background of the ship's structure. Further analysis into how this placement affects the ship's radar cross section will have to occur.

## **5. Alternative AC**

Alternative AC combines alternatives A and C, and received a final Pugh score of 0, which ranked 5<sup>th</sup> out of 8 alternatives. It received no extreme results across the five criteria. Alternative AC is the only case where all scores were nominal, which might be a favorable option to the stakeholder. Although one of the lower ranking alternatives, when delving deeper into the technical details this alternative may easily be one of the top. Alternative A and C as a single HEL are both considered great alternatives, and when you combine the two, the result is even better. Even though the Pugh results do not recommend this alternative highly, there are well more positive aspects than the negatives. Alternative A has the custom modification to fit the HEL's ESM and TSM inside the skin of the ship. Placing components within the ships interior is extremely beneficial in preserving the components from the corrosive sea environment. In addition, the positioning closer to the centerline of alternative C ensured the turbulence would be minimal, if any, coming from the exhaust stacks.

Alternative AC does not escape the process unscathed; however, as a considerable amount of de-confliction is required with both forward and aft HEL mounts in order to conduct an engagement. Up forward, the HEL must de-conflict existing work and personnel on the forecastle, whereas the aft HEL must de-conflict any possible flight operations that may occur. Without these hazards assessed, the ship could put personnel and critical aviation equipment at risk without coordination with the HEL. Due to the weights of the evaluation criteria, the results become skewed as the primary determining factor was with the azimuth and elevation coverage. Alternative AC was in the middle of the road in that criterion, whereas it was a better option for different criteria, but given the

weighted criteria, it fell toward the bottom of the alternatives. Further study is required to determine performance data, modification requirements, etc., to see if this is a viable and highly recommended alternative.

## **6. Alternative AD**

Alternative AD received a final Pugh score of 0.25, which ranked 2<sup>nd</sup> out of 8 alternatives. Alternative AD combines individual alternatives A and D. It received one extreme result across the five criteria ranking best for the azimuthal coverage criterion. Alternative AD differed slightly from alternative AC in that AD scored nominally across the board with the additional score impact to a favorable azimuthal coverage.

Alternative AD's combination took two middle ranked individual placements and combined to form the second best overall alternative. The reason why this dual alternative scored so well is because when one individual placement was weak in a particular criterion, the other placement scored strong in its ranking. Another positive for this alternative is the custom modification to fit alternative A's ESM and TSM inside the skin of the ship. Placing components within the ships interior is very helpful to preserving the components from the corrosive sea environment. Minimizing the number of exposed components should also help to reduce the RCS of the ship.

A negative for this alternative was the removal of an existing weapons system, the 30 mm gun. The goal of each alternative was to find a placement that did not take away from any existing weapons capability. Unfortunately, the aft mount for alternative AD does just that, whereas alternative AC preserves the 30 mm gun capability. Another factor to consider is the performance of the aft mount because it is directly behind the ship's exhaust stacks. The exhaust has the potential to degrade the laser's performance. Although the forward mount was a positive because most of HEL system is inside the ship, perhaps the most important part is in a vulnerable position. The TLCM's placement for the forward mount is placed on the forecastle, which is one of the lowest external heights on the ship. The forward mount's TLCM position increases the exposure to direct sea spray. Not only will the laser's performance degrade when operating during dynamic maneuvering, but the equipment will also require more maintenance.

## **7. Alternative BC**

Alternative BC received a final Pugh score of 0.10, which tied for 3<sup>rd</sup> out of 8 alternatives with alternative B. Alternative BC combines individual alternatives B and C. It received two extreme results across the five criteria ranking worst for the shipboard operations criterion and second best for the elevation coverage criterion. Alternative BC had the favorable score for elevation coverage, weighted as one of the two most important criteria, while having a negative score in the least of the two important criteria. Depending on the stakeholder decisions, this alternative could remain viable.

Alternative BC's combination of two very practical placements and laser coverage capability make it a very possible option. The aft placement is offset from the stacks, which should increase laser performance, and it retains the 30 mm gun capability. The forward placement avoids the possibility of the laser's beam directly striking personnel in the eye because it sits above the pilothouse. The laser will most often operate at general quarters or other conditions when most if not all personnel are stationed within the ship. The positives for alternative BC truly makes this placement a dual threat.

The negatives for alternative BC also exist even though it ranked 3<sup>rd</sup> out of 8. They include accommodating new components, more wires, increased RCS, and de-confliction with flight operations. Neither of the placements will occupy a position where a current system exists. For this reason, modifications to the ship will have to occur. The addition of a new system also means supporting accessories will accompany the placement, which include cables, wires, and structural supports. The external placement may have an effect on the RCS, so an analysis to determine this effect will need to occur. Lastly, the aft HEL's operation may have to cease in the event of an emergency during flight operations.

## **8. Alternative BD**

Alternative BD received a final Pugh score of 0.65, which ranked 1<sup>st</sup> out of 8 alternatives. This alternative combines alternatives B and D. It received three extreme results across the five criteria ranking second best for the shipboard operations and azimuthal coverage criteria and best for the elevation coverage criterion. Alternative BD was the only alternative to receive multiple positive individual Pugh scores with no

negative impacts, which accounts for its' overall rank. However, the Pugh matrix results do not automatically equate to a final recommendation for alternative BD because there are other factors to consider. Table 17 includes a sampling of other factors that were not covered by the evaluation criteria analyzed using the Pugh matrix method. This sampling of factors points to impacts of and on the alternatives that one should consider before selecting any single alternative as the best.

Table 17. Sampling of Other Factors

| <b>Sampling of Other Factors</b>                                                                                                                                                                                                                                                                                                                                                                                                           | <b>Alternative(s) Affected</b> |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|
| Protection from weather and combat damage; reduced impact from corrosive sea environment                                                                                                                                                                                                                                                                                                                                                   | Alternative A                  |
| Reduced impact on ship's RCS relative to other alternatives                                                                                                                                                                                                                                                                                                                                                                                | Alternative A                  |
| Potential re-use of cabling, wiring, framing when replacing 30 mm gun                                                                                                                                                                                                                                                                                                                                                                      | Alternative D                  |
| Increased impact from crashing waves; more frequent, near-continuous sea spray                                                                                                                                                                                                                                                                                                                                                             | Alternative A                  |
| Risk of personnel hazards from operation of HEL                                                                                                                                                                                                                                                                                                                                                                                            | All                            |
| Increase to ship's RCS; additional cost from addition of PCMS to components                                                                                                                                                                                                                                                                                                                                                                | All                            |
| Risk related to weight distribution from containers on decks not designed for the weight                                                                                                                                                                                                                                                                                                                                                   | All                            |
| Challenge adding additional wiring and cabling to support HEL components above bridge                                                                                                                                                                                                                                                                                                                                                      | Alternative B                  |
| Potential additional complexity and cost to re-design 30 mm gun placement to support HEL                                                                                                                                                                                                                                                                                                                                                   | Alternative D                  |
| Coordination of operations and safety before, during, and after flight operations                                                                                                                                                                                                                                                                                                                                                          | Alternatives C and D           |
| Coordination/de-confliction of operations between HEL and other ship's weapons (i.e., 30 mm gun barrel being hit by laser beam, HEL components within fall pattern of expended 30 mm shell casings; timing and tactical engagement decisions during simultaneous engagement on same target or multiple targets)                                                                                                                            | All                            |
| Potential lack of desired net capability gain by adding HEL but removing 30 mm gun                                                                                                                                                                                                                                                                                                                                                         | Alternative D                  |
| Pugh matrix method results do not include the cumulative effects of the evaluation criteria due to the application of weighting. An alternative may have excellent coverage but also be near to sources of turbulence, environment, and shipboard operation impacts such that it suffers the cumulative effects of all three, truly limiting the HEL performance even though it has the capability to nominally provide excellent coverage | All                            |

Alternative BD is a perfect example of the Pugh scores being undeservedly high. The positive aspects of the combination of alternatives B and D display better results than the negatives of the dual mounts, yielding misleading results. As with alternative AD, you are again replacing the 30 mm gun mount, which decreases the overall defense of the ship. On top of replacing the weapon, alternative D has the worst possible position suffering the effects of turbulence given its close proximity to the aft exhaust stacks. As previously discussed, the effect of the turbulence on the operation of the HEL cannot be overlooked.

Results such as these are difficult to demonstrate the true effect of the Pugh analysis without looking at each alternative and identifying underlying concerns. By delving into the technical details, we found that the reason this alternative was ranked highest was due to the weighted values of the evaluation criteria. The azimuthal and elevation coverages shared the highest weights and alternative BD had the largest combined coverage, resulting in the highest score. Had the weights been distributed differently, (i.e., the highest weight in the turbulence and ship environment criteria) the results would be significantly different and alternative BD may easily have been a lower candidate. Further studies in the exact performance effects of turbulence and simulation against threats is desired to ensure the best alternative is selected, but with the current Pugh results based solely on the given evaluation criteria, alternative BD remains on top.

## **C. SUMMARY**

While the results from evaluation of the Pugh matrix clearly show that alternative BD is the best choice, they required further context in the form of individual alternative characteristics from outside the bounds of the evaluation criteria. The context for this more comprehensive analysis provided the clarity necessary to consider the alternatives in proper comparison to one another.

## **V. RECOMMENDATION AND AREAS FOR FURTHER STUDY**

For the work completed in the systems engineering process, a recommended path forward, or multiple, different viable paths often arise in accordance with the data and analysis. Often, the resultant recommendations are expanded to include additional insights acquired through the process that highlight insufficiencies in data or understanding, which preclude potentially more desirable solutions. The following recommendation provides the path forward as dictated by the analysis, followed by areas proposed for additional research and study.

### **A. PROJECT OBJECTIVE QUESTIONS**

Throughout this case study, five questions provided focus and supported accomplishment of the project objectives presented in Chapter I. The answers to these questions follow:

#### **1. What Are the HEL Placement Possibilities on the LPD 17?**

Eight placement alternatives were identified through use of: LPD 17 scaled ship drawings using dimensions for each of the three major SSL-TM components, TLM, ESM, and TSM. Guided by logic, knowledge of naval shipboard operations, and limited knowledge of topside integration considerations, each alternative was selected and a set of individual scaled drawings were created.

The potential options were limited to topside locations for several reasons. The first reason was due to difficulties of visualizing the available space within the ship using only the scaled ship drawings. The second reason was due to a concern for the component sizes that may require redesign and their ability to fit between either two decks or levels. One scenario discussed the feasibility of placing the ESM and/or TSM in the overhead of the well deck. Assuming the HEL component placement within the well deck overhead had no limiting impacts to daily operations, this alternative raised additional safety and maintenance concerns. The additional concerns included scenarios such as safely accessing the components via an overhead catwalk, the risk of affixing a multi-ton Conex box above

a personnel and work transit area, the ability to withstand frequent periods of intense sea spray from landing craft air cushion vehicles, and continuous high humidity all tainted by residual petroleum-based effluents.

Although the stakeholder requested to focus on adding capability and not remove any existing weapons systems, the 30 mm gun mount was identified as a potential placement for the TLCM. This placement was kept in the study based on its potential systems engineering value, as it presented the need to consider trade-offs. Additionally, it was believed that by including this placement, the results might inform other ship integration efforts.

## **2. What Are the HEL Placement Priorities?**

In the bounds of this case study, the HEL component placement priorities were determined to be physical fit followed by coverage (in azimuth and elevation), vulnerability or exposure to the effects of turbulence, environment, and shipboard operations in this order. Environment and shipboard operations had equal weighting. No alternative was viewed concerning these priorities, until it had first been seen to satisfy the relevant system requirements.

The physical fit of the HEL required the component dimensions to be no greater than the specified location's available space. When the HEL components fit into a designated space, proportional shapes were designed and added to the scaled ship drawings. Viewing the proportional HEL components and their placements within the various scaled ship drawings aided in the azimuthal coverage measurements. The proportional HEL components on the scaled ship drawings also aided in the identification of possible blockages due to the ship's structures. The laser's coverage arc was applied to the drawing after the blockages were identified. Finally, the azimuthal coverage was measured and annotated upon the drawing. A similar procedure was used for elevation coverage. Each alternative's exposure to turbulence effects was determined by measuring its furthest distance from the ship's deck edge using the scaled ship drawing. The distance measurement was applied to the associated drawing for each alternative. For exposure to the environment, the distance to the nearest exhaust stack was measured for each

alternative and then annotated on the drawing. A similar procedure was used for exposure to shipboard operations (shock, vibration, and others) except the distances to the nearest 30 mm gun and RAM launcher were used; then applied to the drawings.

Measures that are more precise could have been performed for these evaluations; however, they were beyond the scope of this case study. One such example is ascertaining the difference in environmental effects for the alternative positioned on the forecastle. The forecastle alternative receives sea spray and pounding from waves breaking across the bow with greater frequency and intensity than any other alternative. Lastly, there was limited discussion as to whether vulnerability to combat damage ought to be included as a priority. With every alternative placed topside, each faces the same risk of combat damage. Thus, nullifying the value of combat damage as a priority. Any other means of making a determination suitable for prioritization was beyond the scope of this case study.

### **3. Is There an Advantage to Integrating Multiple HELs onto an LPD 17?**

An underlying driver of our objectives included the possibility of integrating multiple HELs onto the LPD 17. As multiples of capability are desirable, the stakeholder requested consideration of this as well. The factors relevant to identifying the location of a second HEL included the ability to satisfy SWAP-C factors, meet the 360° coverage requirement, and obliging by the placement priorities. The critical factor allowing consideration of a second HEL was the LPD 17 class ship's capability to support the additional power and cooling needs.

Once the locations and alternatives were established, an evaluation of alternatives was conducted. The results were useful in understanding advantages of integrating multiple HELs onto an LPD 17 class ship. A dual HEL alternative increases the LPD 17 class ship's defensive coverage in both azimuth and elevation. With the additional HEL, there is another aspect related closely to coverage and that is the case for simultaneous firing by both HELs.

#### **4. What Are the Integration Challenges Involved?**

The challenges of integrating a HEL or multiple HELs are significant. In following from earlier answers, the initial and most significant integration challenge revolved around SWAP-C factors. Any HEL must fit in harmony with other ship systems and the host ship must be able to provide the services required for operation of the HEL. Given those are satisfied, the next challenge is to balance position with coverage to ensure desired coverage is achieved. The evaluation criteria point to another set of integration challenges. These challenges required consideration of the effects of turbulence, shipboard operations, and the maritime environment on HEL performance.

The SE process executed in this case study led to the discovery of other challenging impacts and integration considerations. There are concerns for numerous hazards introduced through the process of integrating the HEL onto the LPD 17 ship class. There is also the question of achieving desired performance versus the indicated threats. Both of these challenges require in-depth investigation and are discussed in areas for further study.

One final challenge that deserves mention has to do with consideration of tradeoffs when faced with the option of removing an existing weapon system of a given capability and replacing it with a HEL of potentially different capability. Although a last resort to the stakeholder, until the trade studies are complete it is impossible to know whether such replacement may result in a sufficient net increase of capability as to be desirable.

#### **5. What Is the Most Ideal Integration Alternative?**

From the Pugh matrix in Table 16, alternative BD received the highest total score. Understanding the limitations of this case study and the subsequent analyses using the Pugh matrix method, this does not adequately represent the ideal integration alternative. The Pugh matrix returned alternatives BD and AD with the top two scores; each include alternative D, which replaces the 30 mm gun. The next two highest ranked results were alternatives BC and B, both of which retain the 30 mm gun. Of these, alternative BC places its aft mount nearer to the centerline, resulting in less of an impact on ship's stability. Alternatives BC and B also provide for a greater distance between the HELs and the nearest exhaust stacks.

Based upon the interpretation of this additional information, the solution closest to ideal lies with alternative BC. As will be seen in the recommendation to follow, this case study has recognized limitations that prohibit making an absolute determination for selection of the best integration alternative.

## **B. RECOMMENDATION**

Given the analytical results presented in Chapter IV, it is clear that pronouncing a distinct alternative as the recommended best option would be premature. The scope of this analysis ideally would allow for selecting a “best” alternative based on the admittedly limited evaluation criteria. Strictly based upon the outcome of the Pugh matrix method, alternative BD would be the only choice. However, the study did not account for other important factors such as those provided in Chapter IV, Table 17. As an exercise in the application of newly acquired systems engineering knowledge, it bears reporting that the artifacts created carried the effects of broad-based assumptions, data-gathering constraints, and toolset limitations cascading forward to each subsequent step. The principles of systems engineering were obliged in regards to performance while cost and schedule remained necessarily stricken from consideration. Additionally, a typical integration planning effort, as opposed to an academic case study, would naturally have availed itself of necessary and sufficient data from primary sources along with the right tools, expert staffing, and resources while working to bring about collaboration across the pertinent systems and programs. It is with this explanation and understanding that the recommendation that has resulted from this case study is to review, refine, and repeat a similar SE process with new and revised evaluation criteria evolved from a more comprehensive set of system requirements. A secondary recommendation is to complete a sensitivity study ensuring the weighted values for each evaluation criteria clearly align with intent of the study. Finally, in conjunction with these recommendations, it is highly encouraged that the following areas for further study receive full consideration for funding and resource support.

## **C. AREAS FOR FURTHER STUDY**

- Hazard identification and risk assessment
- Performance vs. threat
- Physical measurements
- Impact of shipboard operations
- Shipboard turbulence studies
- Shipboard environment studies
- Weapons coverage and blockage mapping

### **1. Hazard Identification and Risk Assessment**

Hazard identification and risk assessment are vital components to understanding the integration and making appropriate decisions and the first and foremost priority is personnel safety, followed closely by protecting equipment from damage. The HEL weapon system includes many aspects hazardous to personnel and, as with all shipboard weapons and electro-mechanical equipment, such things as electrical safety, hazardous materials, working aloft, eye safety, hazards of electro-magnetic radiation to personnel must be addressed in order to make determinations for new or modified procedures, the need for PPE, and more. Shipboard weapons and equipment themselves require protection as well. Considerations include such things as circuit protection, shock isolation, hardening for components at risk from electro-magnetic pulse, interference caused by emissions from other systems, overheating, and hazards of electro-magnetic radiation to ordinance/fuel hazards and falling within the pointing or firing cutouts of weapons.

### **2. Performance vs. Threat**

Performance of the HEL must be assessed against the threats assigned to ensure the integrated system can achieve its desired performance against the identified threats. Threat data of appropriate fidelity should be used to develop scenarios suitable for ground or lab

testing, at-sea testing and live, virtual, and constructive modeling and simulation. Threat characteristics should be considered in developing criteria for success versus each threat. Performance analysis should pose the integrated system against the UAS, small boats, and subsonic missile threats according to the notional scenarios to determine the suitability of the HEL against the comprehensive system requirements. Scenarios should consider each threat individually and multiple threats in combinations and permutations as well as the HEL alone and the HEL in various combinations with other ships weapons. Execution of these scenarios will need balanced against resources and prioritized for maximum value at informing integration decisions.

### **3. Physical Measurements**

The physical measurement of shipboard spaces needs to occur, so a determination can be made if HEL components will fit according to the placements desired. As witnessed in alternative A, the HEL's components receive modifications to fit within the ship's interior. Understanding the ship's footprint and potential structural modification needs as well as cable and piping runs will help set requirements for a modified ESM/TSM design. Rather than simplified use of scaled ship drawings, new detailed designs that include all of the ship's features with HEL components in place can be created by utilizing computer-aided design software. A combination of computer-aided design software and modeling and simulation software can simulate the effects of dynamic forces. Additionally, dynamic calculations are important because they reveal sources of instability based on varying situations. Understanding the precise placement of HEL components and their weights can be used to calculate righting arms and righting moments necessary to understand how their addition to the ship effects overall stability so that necessary changes can be made to the damage control system and drawings. The study of physical measurements aided by software will allow designers to determine the most optimal arrangement for HEL components in terms of stability.

### **4. Impact of Shipboard Operations**

Impact of shipboard operations upon HEL performance is a concern. Numerous shipboard operations can disrupt the HEL's performance every day. Factors to consider

include shock, vibration, sound, and electronic interference. The ship operates in an unpredictable sea environment. During rough sea states, the ship can violently pitch up then come crashing down into the surface of the water. The ship operates large main diesel engines and ship's service diesel generators that induce sound and vibration throughout the ship. The ship operates multiple radars to maintain its situational awareness. The radars may disturb the operation of the HEL through electro-magnetic interference. Each operation may play some role in altering or interrupting the laser beam resulting in shortened effective range, expanded beam diameter, instability or jitter when on target, and even missing the target. It is important to understand how their effects limit performance against different targets in varying scenarios and whether there are solutions available to overcome these limits. Investigating the effects of these operations on the HEL alternatives is highly recommended.

## **5. Shipboard Turbulence Studies**

Shipboard turbulence studies would serve well in understanding the sources and effects of turbulence on the HEL alternatives. Studies are underway at the NPS physics department to investigate turbulence and its effects on HEL performance in a shipboard environment. Early feedback indicates that deck heating on sunny days provides sufficient temperature differentials between the air rising off the hot decks and the cooler ambient air. These differentials cause turbulence within affected air columns. When the laser beam passes through an affected air column, it experiences turbulence. It is understood, in general, that turbulence will have undesirable and varied effects upon laser beam effectiveness in transit and at the target. In addition to the hot decks, there are other heat sources with the potential to initiate turbulence including other ship's structures, exhaust stacks, and exhaust vents. Unless the NPS study expands to address all of these, they will require further investigation. Ultimately, understanding and representing the combined effects for all sources of turbulence requires mitigation through intelligent integration decisions. The research and integration decisions are beyond the scope of this work.

## **6. Shipboard Environment Studies**

Shipboard environment studies are recommended in relation to understanding the capabilities and limitations of the HEL alternatives. The Navy operates in very harsh environments. The sea and salt air are corrosive to the vast majority of the ship's hull, superstructure, electrical and mechanical systems, electronic equipment and auxiliary or accessory components. The effects require time and attention to maintain all in working order. Typically, when an aircraft deploys a laser at sea, the weapon is utilized at a higher altitude away from much of the sea spray, reducing some of these effects. Shipboard lasers are much closer and their exposure is nearly constant. During aggressive ship handling and combat maneuvering, the HEL has an even greater chance of exposure to seawater and salt spray. At times, the sun also beats down on the components while they are wet with salt water. The sun causes the salt to crystallize as the water evaporates leaving the component coated. Firing a laser through a lens coated with salt crystals is going to have an impact on the laser beams quality and depending upon the circumstances there could be damaging effects to the lens or other HEL components. Additionally, the shipboard environment includes all manner of weather phenomena from extreme hot and cold, to humidity, fog, sand and dust storms. While the salt water effects appear to be the most concern over the long-term, these others can also have effects on HEL alternative performance and should not go without investigation.

## **7. Weapons Coverage and Blockage Mapping**

Weapons coverage and blockage mapping is another major factor that warrants further study. To determine the best alternative for the HEL one must fully understand the weapons' coverage given its position and precisely accounting for blockages caused by the ships' superstructure, topside equipment, and other weapons. The mappings should provide a total azimuth coverage picture, total elevation coverage picture, and a combination of both. In the hypothetical case where a weapon sits at the highest point on the ship, it would be theoretically possible to end up with a combined coverage picture of not less than a complete hemisphere. Of course, this is never actually the case in real-world situations, thus the need for understanding where the blockages create the need for cutouts.

The purpose of mapping the firing cutouts including blockage zones is to prevent a weapon from pointing at or inadvertently striking another part of the ship during an engagement as well as to understand the capabilities from a tactical standpoint. The HEL requires precise information concerning its limitations so projected target bearing and elevation are calculated, based upon target motion, in order to interrupt firing in a timely manner. In addition, the combat system needs firing cutout information. This allows it to avoid passing targets to the HEL when it cannot engage them due to the cutout and both the HEL and other weapons are utilized to maximum efficiency. A study is essential in determining the effect of the total ship coverage based on the mapping of the cutouts. In order to conduct this study, simulations and testing will be required against targets of varying difficulty to understand engagement limitations and better plan and train the appropriate tactics, techniques, and procedures.

#### **D. SUMMARY**

Adding one or more HELs to the LPD 17 class ship will greatly improve the capability of the ship, but it is not to be at the expense of another weapon. The results from the simulations and testing will point out any coverage limitations that are introduced by adding each HEL alternative in their respective positions. Again, execution of the testing and simulation needs balanced against resources and prioritized for maximum value at informing integration decisions.

In summation, once these areas are adequately studied, the Navy able to undertake the planning and execution of integrating a HEL weapon system into an LPD 17 class ship. In fact, this case study in combination with the results of the studies above should be more than suitable to inform the earliest stages of preparation for integration of a HEL weapon system on nearly any surface naval vessel with slight adjustments and tailoring.

## **APPENDIX A. HISTORY OF HEL SYSTEMS**

Only 60 years or so since the first working laser came into being, High Energy Laser (HEL) weapon systems are on the cusp of becoming an operational technology. In discussing HEL weapons systems from a historical perspective, one could reach back to the fundamental physics research to form a backdrop. The 1917 paper by Albert Einstein on the quantum theory of radiation was the theoretical premise underlying stimulated emission of radiation (SER) in LASER (American Physical Society 2005). In 1960, Theodore Maiman created the first working laser at Hughes Research Laboratory (American Physical Society 2010). However, it seems more practical to begin with discussion of the earliest high energy weapon systems.

The following chronology depicts a general history of HEL weapon systems:

- (1968) “Directed Energy Directorate of Air Force Research Laboratory (AFRL), was authorized to begin a new program on building and testing a CO<sub>2</sub> gas dynamic laser.” (Global Security 2011)
- (1973) AFRL conducted two tests on 13 and 14 November 1973. “The two tests marked the first time that aerial targets had ever been destroyed by a high energy laser.” (Global Security 2011)
- (1975) “Airborne Laser Laboratory (ALL) (NKC-135A) flight tests began in January 1975.” (Global Security 2011). The laser “footprint” is depicted in Figure A1.

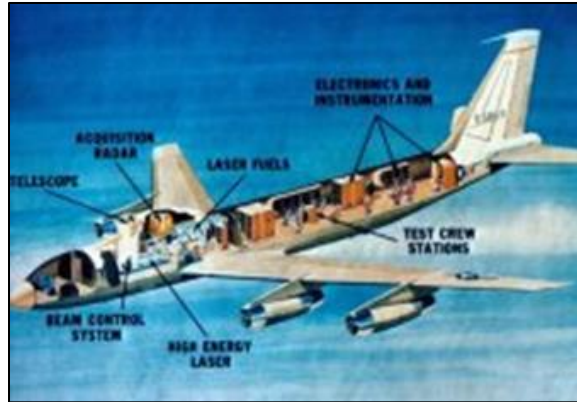


Figure A1. Airborne Laser Laboratory (ALL). Source: Global Security (2011).

- (1983) “ALL program was a resounding success, proving that the goal of airborne anti-missile defense was indeed realistic.” (Global Security 2011)
- (Mid-1980s) “Mid-Infrared Advanced Chemical Laser (MIRACL) developed in the mid-1980s...many believe that MIRACL was the first and only successful laser weapon system developed by the Navy prior to the Navy laser weapon system (LaWS).” (Olson 2012)
- (1991) “Alpha, an HF laser, was the baseline technology for the space-based laser readiness demonstration (SBLRD). In 1991, the Alpha laser demonstrated megawatt-class power levels similar to MIRACL, but in a low-pressure, space operation environment. Alpha demonstrated that multi-megawatt, space-compatible lasers can be built and operated.” (Olson 2012)
- (1996) “In 1996, the Department of Defense awarded team airborne laser (ABL) a \$1.1bn [program] definition and risk reduction (PDRR) contract for the development and test of an airborne laser weapon system.” (Air Force Technology n.d.)
- (1996-2000) “Tactical high-energy laser (THEL) was designed and built in only four years – from 1996 to 2000” (Northrup Grumman n.d.). It was a

cooperative development between the U.S. and Israel resulting in the system seen in Figure A2.



Figure A2. THEL. Source: Northrup Grumman (n.d.).

- (2002) “Modification of the aircraft (YAL-1), involving installation of the ABL turret in the aircraft’s nose and modifications to accept the laser, optics and computer hardware, was completed in May 2002. In July 2002, the modified aircraft took the first of a series of test flights” (Air Force Technology n.d.). The modified YAL-1 is shown in Figure A3.



Figure A3. YAL-1 in Flight. Source: Airborne-Laser (n.d.).

- (2002) “The U.S. Defense Advanced Research Projects Agency (DARPA) launched the HELLADS development [program] in 2001. The agency has allocated about \$75m towards the development, with the [program] to be completed in five phases. The initial two stages, which were completed by 2002, found the liquid laser system to be feasible” (Air Force Technology n.d.). Figure A4 is an illustration of the High-energy liquid laser area defense system (HELLADS).



Figure A4. HELLADS Photo Illustration (DARPA). Source: Whittle (2015).

- (2010) “The first real laser weapon was the U.S. Air Force/Boeing YAL-1 airborne laser (ABL), a megawatt-class chemical oxygen iodine laser... mounted inside a modified Boeing 747-400F jumbo jet. Designed to shoot down tactical ballistic missiles during their boost phase, it first was test-fired at an airborne target in January 2010 and soon after intercepted three test missiles, destroying two of them.” (Wilson 2017)
- (2010) “The U.S. Department of Defense...awarded long-term contracts to Raytheon and Lockheed-Martin aimed at developing a 100kW weapons-class laser system [on June 24<sup>th</sup> and 28<sup>th</sup> respectively]. Under the robust electric laser initiative (RELI), Lockheed’s MS2 Integrated Defense Technologies unit will work on the project, which has an estimated

completion date of December 2016” (Northrup Grumman 2010). Figure A5 shows RELI mounted on a UH-60 helicopter.



Figure A5. RELI. Source: Northrup Grumman (2010).

- (2010-2012) “A smaller, lighter and more efficient Gen 2 system was built and tested [by General Atomics Aeronautical Systems, Inc. (GA-ASI)] in 2010–12 for the Pentagon’s HEL Joint Technology Office.” (Warwick 2015)
- (2011) “Third phase of [HELLADS] development was completed. It involved successful testing of the laboratory scale laser module which replicates the same operational capability and geometry of the final weapon system.” (Air Force Technology n.d.)
- (2011) “GA-ASI has been awarded a contract...for development of the complete demonstrator laser weapon system (DLWS). The demonstrator system represents phase four of DARPA’s high-energy liquid laser [defense] system (HELLADS)... The DLWS includes a 150KW laser with integrated power and thermal management systems...” (Army Technology 2011)
- (2014) “The Navy...hit a milestone in the summer of 2014 with the deployment of the [30 kW] LaWS aboard the USS Ponce.” (McCaney 2015)

- (2014) “In April 2014, the Army awarded Lockheed Martin...a \$25 million contract to build a 60 kW fiber laser ruggedized to withstand the [high-energy laser-mobile demonstrator] (HEL-MD) being driven off-road.” (Hecht 2014). Figure A6 shows the HEL-MD.



Figure A6. HEL-MD. Source: Hecht (2014).

- (2015) “Lockheed Martin reported March 3, 2015 that a 30-kilowatt fiber laser weapon system successfully disabled the engine of a small truck during a recent field test...Known as ATHENA, for advanced test high energy asset, the ground-based prototype system burned through the engine manifold in a matter of seconds from more than a mile away” (Wilson 2017). Figure A7 shows the effects of ATHENA.



Figure A7. Effects of ATHENA. Source: Wilson (2017).

- (2015) “GA ASI...announced that the HELLADS completed the U.S. government acceptance test procedure... [Next] the laser will undergo an extensive series of live fire tests against a number of military targets.”(General Atomics-Aeronautical Systems Inc. 2015)
- (2017) “In March 2017, Space and Missile Defense Command announced completion of acceptance testing on the Lockheed Martin 60-kilowatt Spectrally Combined High Power Solid State Fiber Laser...The laser will be integrated with the HELMTT and used in test environments relevant to warfighting applications.” (Wilson 2017) Figure A8 depicts HELMTT.



Figure A8. Artist Rendering of Lockheed Martin 60 kW Laser on a Tactical Vehicle. Source: Lockheed Martin (2017).

- (2017) “The [Lockheed Martin 60 kW-class beam combined fiber laser for the U.S. Army]...proved to be highly efficient in testing, capable of translating more than 43 percent of the electricity that powered it directly into the actual laser beam it emitted.” (Lockheed Martin, 2017)

## APPENDIX B. EVALUATION CRITERIA

Table B1 represents an intermediate step between completed requirements and draft evaluation criteria. Gray shaded rows indicate criteria not suited for use due to being either non-applicable, beyond the scope, or both. Only those criteria used for the conduct of the evaluation of alternatives remain unshaded.

The integrated HEL requirements would be based upon specifics delineated in no less than one formal document. For this project, the specifics are contained in a notional document referred to as the HEL-LPD integration interface control document (ICD).

Table B1. List of HEL Alternatives with Placement Descriptors

|    | <b>Requirement</b>                                                                                                                            | <b>Evaluation criteria in support of evaluation of alternatives</b>                                                                                                                                                                         |
|----|-----------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| R1 | The integrated HEL shall be capable of achieving a mobility kill versus a single hostile Unmanned Aircraft System (UAS).                      | Pk of XX% for mobility kill versus a single hostile UAS. Analysis of a Monte Carlo simulation of a representative scenario.                                                                                                                 |
| R2 | The integrated HEL shall be capable of achieving a mobility kill versus up to X simultaneous hostile Unmanned Aircraft Systems (UASs).        | Pk of XX% for mobility kill versus up to X simultaneous hostile UASs. Analysis of a Monte Carlo simulation of a representative scenario.                                                                                                    |
| R3 | The integrated HEL shall be capable of achieving a mobility kill versus a single hostile small boat.                                          | Pk of XX% for mobility kill versus a single hostile small boat. Analysis of a Monte Carlo simulation of a representative scenario.                                                                                                          |
| R4 | The integrated HEL shall be capable of achieving a mobility kill versus up to X hostile small boats.                                          | Pk of XX% for mobility kill versus up to X simultaneous hostile small boats. Analysis of a Monte Carlo simulation of a representative scenario.                                                                                             |
| R5 | The integrated HEL shall be capable of achieving a total kill versus a single hostile sub-sonic, anti-ship missile.                           | Pk of XX% for total kill versus a single hostile sub-sonic, anti-ship missile. Analysis of a Monte Carlo simulation of a representative scenario.                                                                                           |
| R6 | The integrated HEL shall meet specified reliability requirements assigned to the HEL design without degradation due to integration decisions. | Reliability analysis reflecting achievement of pre-integration HEL reliability requirements <b>after</b> integration. Requires collection of data from all HEL operations on the LPD in an operationally realistic environment. (Because it |

|    |                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|    | (i.e., if the HEL, as designed, had and met a requirement for Operational Availability ( $A_o$ ) prior to integration, then it shall continue to meet that value after integration) | must follow the integration and thus does not support evaluation of alternatives.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| R7 | The integrated HEL shall meet specified maintainability requirements of the HEL as designed, not to be eased or degraded by integration decisions.                                  | Maintainability analysis reflecting achievement of the “as designed” HEL requirements in the <b>after</b> integration configuration. Requires collection of data from all HEL operations on the LPD in an operationally realistic environment. (Because it must follow the integration and thus does not support evaluation of alternatives.)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| R8 | The integrated HEL shall include protection of vital components from effects of hostile weapons (blast waves, fragmentation, directed energy, etc.)                                 | Survivability analysis of the integrated HEL would ideally be conducted on results of live fire test and evaluation. However, it is unlikely that such testing would be approved in this case due to costs and other risks plus it can only be performed <b>after</b> integration and thus does not support the evaluation of alternatives. Modeling and Simulation is the only solution and would be leveraged to emulate particulars of hostile weapon effects.                                                                                                                                                                                                                                                                                                                                                                         |
| R9 | The integrated HEL shall be positioned and installed in a manner to minimize effects of shipboard operations (shock, vibration, etc.)                                               | Inspection and observation (visualization) of planned component positioning and method of installation would be necessary in order to analyze achievement of this requirement. Variety of operations and at-sea conditions would prohibit capturing every possibility. Analysis would benefit from a combination of data from operationally realistic conditions applied in conjunction with modeling and simulation to address missing conditions. A minimally useful criteria for evaluation of alternatives within scope would be to measure the distance between each alternative and the nearest 30 mm gun and RAM launcher as firing of these weapons are known operations which produce effects such as shock and vibration which may affect HEL performance. The nearer to each weapon, the greater the effect on the laser beam. |

|     |                                                                                                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-----|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| R10 | The integrated HEL shall be positioned to minimize effects of turbulence.                        | Inspection and observation for ship-borne causes of turbulence (temperature differential caused by heat sources onboard such as hot exhaust gases from the stacks). Additionally, recent research by the NPS Physics Department indicates that heat rising from hot decks on sunny days can interact with ambient air and create sufficient temperature differentials to induce turbulence. In theory, the length of time or distance the laser beam must travel above these hot decks exacerbates the turbulence effects on the beam. Thus, a minimally useful criteria for the evaluation of alternatives would be to determine the maximum distance for laser beam travel from each alternative before crossing the deck edge. The longer the distance the more opportunity for turbulence to effect the beam.                                                                                                                                                                                                  |
| R11 | The integrated HEL shall be positioned and installed to minimize maritime environmental effects. | Inspection and observation of the HEL's placement with regard to various environmental effects. The laser performance is susceptible to all manner of particulates within the air column in which the beam travels. Some particulates include salt, sand, dust, fog, clouds, and stack gases (including unburnt fuel and carbon from the combustion process). With regard to naturally occurring particulates, alternative placement is unlikely to result in significant differences from the effects on performance. However, the opacity of the stack gases may prevent laser transmission by absorbing energy from the beam, causing the laser performance to degrade, and this effect will be more pronounced when near an exhaust stack. A minimally useful criterion for evaluation of alternatives within scope would be to measure the distance between each alternative and the nearest exhaust stack. The closer each weapon is to an exhaust stack, the greater the negative effect on the laser beam. |

|     |                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| R12 | The integrated HEL shall comply with dimensional constraints of the space designated for it and/or its components based upon placement decisions made in support of the integration.                                                     | Fit would need to be assessed first via high fidelity integration drawings (models/CAD) followed by site visits for physical measurement of the installation space on the LPD and the designated HEL component. No real analysis per se, just measure twice cut once.                          |
| R13 | The integrated HEL shall comply with the weight allowance/budget allotted per component as specified in the HEL-LPD Integration ICD.                                                                                                     | No evaluation criteria applicable for evaluation of alternatives as each position will receive the same components thus same weight. (Unless the VLS version (alternative A) has no “bulkheads” and thus would have less weight, but that would be an obvious positive and needs no analyses). |
| R14 | The integrated HEL and its components shall comply with stability and righting moment limitations as prescribed in the HEL-LPD Integration ICD.                                                                                          | Analysis of each component in its designated position per alternative based upon relation to the ship’s center of gravity.                                                                                                                                                                     |
| R15 | The integrated HEL shall operate when provided with power in accordance with the HEL-LPD Integration ICD.                                                                                                                                | Ground (lab) test of HEL with LPD power consumption emulated for worst case (all vital loads maximized) in various combat scenarios. Configuration must reflect reality.                                                                                                                       |
| R16 | The integrated HEL shall operate when provided with chilled water in accordance with the HEL-LPD Integration ICD.                                                                                                                        | Ground (lab) test of HEL with LPD power consumption emulated for worst case (all vital loads maximized) in various combat scenarios. Although this is worded for power, such scenarios should represent maximum cooling loads as well. Configuration must reflect reality.                     |
| R17 | The integrated HEL shall be capable of slewing and acquiring an initial target track when provided with LPD target track data from the SSDS Mk II combat system. Engagement hand-off will be conducted in accordance with SSDS doctrine. | Analysis needed to determine the timelines before knowing specific solutions to this requirement is outside the scope of this project and would be performed for an actual integration effort.                                                                                                 |
| R18 | The integrated HEL shall comply with the HEL-LPD Integration ICD specifications with regard to prevention of mutual interference across the electromagnetic spectrum between itself and other LPD systems.                               | Lab testing to emulate proximity and variations in operations and activities to approximate operationally realistic scenarios. Testing would need to consider 1 on 1 and combinations of multiple systems to the greatest extent affordable/feasible.                                          |
| R19 | The integrated HEL must provide for tactical point-to-point voice                                                                                                                                                                        | Testing for achievement of this requirement prior to actual installation would be questionable. True status would not be known                                                                                                                                                                 |

|     |                                                                                                                                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | communications between the TWC and CIC, and the TWC and Bridge.                                                                                       | until wiring and interface connections are made. (No evaluation criteria in this case.)                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| R20 | The integrated HEL ship shall be capable of a maximum effective range greater than 3000 yards/2745 meters.                                            | The HEL being capable of achieving the specified maximum effective range is not a useful evaluation criterion for selection of an alternative.                                                                                                                                                                                                                                                                                                                                                                                  |
| R21 | The integrated HEL shall be capable of providing azimuthal coverage of 360° relative for two mounts or greater than 180° relative for a single mount. | Coverage would need to be assessed first via high fidelity integration drawings (models/ CAD) followed by site visits for physical measurement for determination of blockages at each alternative TLCM position. A minimally useful criterion for the evaluation of alternatives would be to estimate the coverage and blockages based upon the scaled ship drawings and estimating the total azimuthal coverage provided per mount. The greater the coverage, the better provided the requirement is satisfied as a minimum.   |
| R22 | The integrated HEL ship shall be capable of providing -5 to 90° coverage in elevation.                                                                | Elevation would need to be assessed first via high fidelity integration drawings (models/ CAD) followed by site visits for physical measurement for determination of blockages at each alternative TLCM position. A minimally useful criterion for the evaluation of alternatives would be to estimate the coverage and blockages based upon the scaled ship drawings and estimating the total elevation coverage provided per mount. The greater the coverage, the better. Provided the requirement is satisfied as a minimum. |

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