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COST ANALYSIS FOR OPERATIONAL AND SYSTEM LEVEL CONSIDERATIONS FOR AN ELECTROMAGNETIC RAILGUN ON AN AMPHIBIOUS PLATFORM

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ABSTRACT

This article investigates outfitting an amphibious platform with an electromagnetic railgun (EMRG), which is a high velocity weapon that can fire projectiles at ranges up to 100 nautical miles. An EMRG would provide the amphibious fleet with offensive capability, as well as defensive capability against surface threats, missiles, and airborne threats. A cost estimate for railgun integration and a cost effectiveness analysis, from both an operational and system perspective, is presented. The cost estimate for EMRG integration is FY20 $134.66M, given a 32 MJ railgun. From an operational effectiveness perspective, hit probability of air targets was found to have a greater impact on performance than any other design characteristic. When balancing cost versus effectiveness, a 10 MJ railgun is preferred to a 32 or 20 MJ railgun. Future work includes modeling and simulation of various concepts of operation.

1 INTRODUCTION

The landing platform dock (LPD) San Antonio class ship serve as sea-based platforms to conduct amphibious operations, specifically transporting and launching air and amphibious assault craft. Due to the nature of these operations, LPDs generally remain within close distance of the shore, which poses a threat to the ship and any of its supported elements. To combat this issue LPD class ships may be outfitted with offensive engagement capabilities. This paper considers the electromagnetic railgun (EMRG), a high velocity weapon that can fire projectiles at targets at ranges up to 100 nautical miles utilizing electromagnetic propulsion rather than traditional propellants. The EMRG would provide offensive capability in the form of naval surface fire support (NSFS) and a defensive capability against surface, missile, and airborne threats. Because the EMRG can provide both offensive and defensive capability, there is a potential increase in operational effectiveness of amphibious ships. This paper investigates the feasibility of that approach and conducts a cost and operational analysis as the basis for a trade-off assessment regarding the impact of integrating the EMRG on the LPD class amphibious ships.

2 BACKGROUND

2.1 LPD Class Ships in Amphibious Operations

For the United States Navy, amphibious forces are task-organized, and their structure is tailored to missions ranging from assault to humanitarian efforts such as disaster relief (Joint Chiefs of Staff 2019). Generally, an amphibious force can be structured as an Amphibious Ready Group (ARG) or an Expeditionary Strike

Group (ESG). An ARG is composed of a landing helicopter assault (LHA) or landing helicopter dock (LHD) ship, a dock landing ship (LSD), and an LPD class ship. An ESG is made up of the same ships and has a surface combatant such as a guided missile cruiser (CG) or destroyer (DDG) for enhanced air and surface warfare capabilities and to provide NSFS for ground forces.

Within the context of either an ARG or ESG, the LPD class ships are multi-mission platforms designed to embark, transport, and land Marine forces (O'Rourke 2020a). They are capable of carrying a variety of amphibious landing craft such as the landing craft air cushion (LCAC), landing craft utility (LCU), amphibious assault vehicle (AAV), and light amphibious resupply cargo (LARC) as well as support vehicles such as armored trucks, bulldozers, and tanks. The San Antonio class LPD is equipped with the Close-In Weapon System (CIWS), Rolling Airframe Missile (RAM), MK-46 30-millimeter cannons, and other crew served weapons in support of surface and air warfare. The ship is intended to operate in a low to medium density, multi-threat environment as part of a task force or independently, provide its own anti-air and limited anti-surface defense, and perform sustained amphibious operations (Department of the Navy 2017).

Each ship in an ARG or ESG has a specific role within the amphibious operations structure. Figure 1 shows the layout of sea-based forces for an amphibious operation. The fire support and NSFS mission are assigned to the DDG or CG. They are positioned no more than 4–5 nautical miles from the shore due to maximum effective range of their main battery. The LSD is responsible for launching AAVs and LCUs, so it alternates position between the transport area and the AAV launching area. The LPD launches LCACs and will be stationed in the cushion launch area (CLA) in either the transport area or the sea echelon area. LCACs have a longer range than AAVs and are faster than LCUs, which allows the LPD to take station further away, if necessary. The command ship, LHA or LHD, may also launch LCACs from the sea echelon area but will retreat to the distant retirement area to perform flight operations. This operational concept may be changed through the introduction of new technologies such as the railgun weapon system.

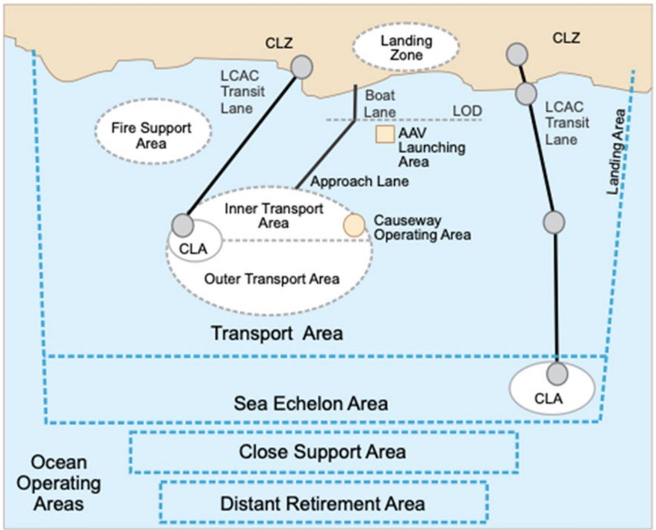


Figure 1: Amphibious Operation Layout of Forces and Operating Areas (from Joint Chiefs of Staff 2019).

2.2 Electromagnetic Railgun

The EMRG is a long-range weapon system that uses stored electromagnetic energy to fire hypersonic projectiles rather than conventional chemical-based propellants (BAE Systems 2014). Magnetic fields are created by an electrical current flowing through conducting rails to accelerate an armature to launch the projectile at speeds up to Mach 7 (Tzeng and Schmidt 2011). The hypervelocity projectile impacts and destroys targets with kinetic energy rather than an explosive warhead. The EMRG also provides improved shipboard safety measures by eliminating the use of gunpowder and other high explosive material within the ship's magazines (Department of the Navy 2017).

The Electromagnetic Railgun Innovative Naval Prototype (INP) developed by BAE Systems at the Naval Surface Warfare Center Dahlgren Division (NSWCDD), is capable of launching projectiles at speeds approaching Mach 6 with a muzzle energy of 32 megajoules (MJ), which equates to a 110 nautical mile range (Department of the Navy 2017). This is an improvement over the currently employed MK 45 5-inch gun mount whose maximum effective range is approximately nine nautical miles. The system can support sustained military operations with a firing rate exceeding 10 rounds per minute and a magazine capable of carrying up to 500 projectiles (Chaboki et al. nd).

This increased engagement envelope suggests that there may be operational utility that can be realized through the integration of the EMRG on LPD class ships. The addition of an EMRG would add to LPD-17's list of operational capabilities some that are traditionally assigned to the CG. This includes providing NSFS support to amphibious ground forces with direct and indirect fires. With firing ranges exceeding 100 nautical miles, a ship can station itself far enough from shore to avoid being susceptible to land-based anti-ship cruise missiles (ASCM) while maintaining the ability to launch LCACs and conduct flight operations. Engagement of air targets would occur at shorter ranges due to the requirement of the EMRG launched projectile to physically strike the target and destroy it with kinetic energy rather than an explosive warhead (O'Rourke 2020b). This also makes Navy planning more flexible due to the elimination of the requirement for an ARG to be augmented with a CG or DDG to provide fire support and area defense.

3 APPROACH

3.1 Cost Estimation

For DoD systems, cost estimated span four phases of a system's life cycle: Research and Development (R&D), Investment or Procurement, Operations and Support (O&S), and Disposal (Secretary of Defense 2020). Historically, while the majority of costs are incurred in the O&S phase, they are obligated in the R&D and investment phases, necessitating quality cost estimates early in the system development life cycle. Within the DOD's acquisition process is a requirement to conduct a cost analysis at each milestone review (Boito et al. 2018). The four most common methods the DOD uses for developing a cost estimation are: analogy, parametric, engineering build-up, and extrapolation based on actual cost (Government Accountability Office 2020). The EMRG is currently in the early stages of system design, accordingly parametric and actual cost approaches cannot be employed. This paper will employ a combination of analogy and engineering build-up approaches to develop cost estimates for the EMRG on the LPD.

3.2 Operational Analysis

To provide detail regarding the design configuration decisions for the EMRG an operational model was created in the discrete event simulation modeling program ExtendSim. ExtendSim was chosen based on the expertise of the authors as well as familiarity with a previous operational study conducted by (Ciron et al 2020). That effort analyzed the utility of an LPD equipped with an EMRG in support of an ATF conducting amphibious assault. This paper expands that modeling effort by varying the characteristics of the EMRG, within a modified ARG, that (Ciron et al. 2020) identify as well suited to take advantage of the EMRG to develop an integrated cost versus effectiveness analysis.

4 COST ESTIMATION

4.1 EMRG Definition

The first step in developing a cost estimate for the railgun using the engineering build-up method is to decompose the various components of the weapon system. A study conducted by (Department of the Navy 2018) breaks the EMRG into a gun mount made of a barrel and gun electronics and a pulsed power module made of a pulsed power supply and pulsed power transfer. That study examined the integration of the EMRG on DDG class ships, accordingly an analogy is necessary to appropriate estimate the cost that the EMRG may have on LPD class ships. Scaling factors are used to alter the cost of the analogous weapon systems to reflect changes in design, material, and manpower.

4.1.1 Integration Factors

The Naval Center for Cost Analysis (NCCA) sets policies and procedures for conducting cost estimates, cost analysis, and economic analysis and for reporting cost estimates and comparisons to the budget. The NCCA publishes a cost factors handbook (Naval Center for Cost Analysis 1992), which provides guidelines and cost estimating relationships (CER) used for program cost estimates. Cost factors define the percentage of funding allocated to design, hardware, software, program management, and integration. These cost factors are adapted from historical data to reflect differing challenges across the system lifecycle, such as from initial integration and assembly to training or program management. Table 1 presents two categories of cost factors: cost integration factors for lifecycle phases and cost integration factors for historical systems. These categories of cost estimates serve two distinct purposes for this analysis. The life cycle phase integration factors are used to develop a baseline cost estimate for the EMRG. The integration factors for similar systems are used to highlight the uncertainty associated with the estimate. Specifically, this analysis uses the NCCA integration factor for engineering and manufacturing development, defined by the NCCA as 17.3%. Assessment of comparable historical systems suggests that this likely constitutes something closer to a lower bound on the cost, Table 1 shows a range of 15.9% to 40.9% for these comparable systems. Accordingly, the integration factors for life cycle phases are used along with the engineering level data for the EMRG to develop an initial cost estimate for the EMRG system. Subsequently, the integration factors for historical systems are used to calculate a range for the final cost estimate for the EMRG integrated onto an LPD class ship.

Table 1: Integration Factors by Life Cycle Phase and System

	% Integration Factor
Life Cycle Phase	
Engineering & Manufacturing Development	17.3
Production	8.3
System	
AN/SLQ-32(V)6 Electronic Warfare System	40.9
AN/SLQ-32(V)7 Electronic Warfare System	25.6
High Energy Laser with Integrated Optical-Dazzler and Surveillance (HELIOS)	15.9
Advanced Gun System (MK 51 AGS)	35.2
Independence Class LCS Combat Systems Upgrades	36.8
Freedom Class LCS Combat Systems Upgrades	37.9

4.1.2 Normalization for Inflation

Normalization provides consistent cost data by neutralizing the impacts of external influences (Wise et al. 2011). To account for inflation and compare the cost data across reporting years, the Joint Inflation Calculator, developed by the NCCA, is used to normalize cost data between the base year reported in the reference document and fiscal year 2020. Note that the inflation rates differ across system lifecycle categories. This paper uses Composite Research, Development, Test, and Evaluation (RDT&E), as defined in (Wise et al. 2011) for the EMRG. Because the initial cost estimate for the EMRG on the DDG was calculated in fiscal year 2018, an inflation factor of 1.0402 was used to normalize to fiscal year 2020.

4.1.3 Initial Estimate

The initial estimate for the EMRG system is based on (Department of the Navy 2018), where the total cost of the EMRG was estimated, in fiscal year 2018, as $110.36M. Using the inflation factor of 1.0402 and an integration factor for engineering and manufacturing development from Table 1 of 17.3% an initial cost estimate for the EMRG, in fiscal year 2020, is $134.66M. Assessment of this historical integration factors for similar systems presented in Table 1 suggests that this estimate, which is based on EMRG employment on a DDG class ship, likely represents a lower bound for the EMRG aboard an LPD. Using those integration factors from comparable systems, alternative cost estimates are generated to highlight the range of potential total costs for the EMRG when integrated onto an LPD. Table 2 presents a visualization of the cost ranges for the EMRG aboard an LPD using a range of integration factors from Table 1 of 10% to 40%.

Table 2: Cost Estimates for EMRG Integrated on LPD

Integration Factor (%)	Integration Cost (FY20$M)	Total System Cost (FY20$M)
10	11.48	146.14
15	17.22	151.88
20	22.96	157.62
25	28.7	163.36
30	34.44	169.1
35	40.18	174.84
40	45.92	180.58

4.1.4 Cost Estimates for EMRG Variants

The cost estimates from Table 2 are based on a baseline power configuration for the EMRG. Specifically, the data from (Department of the Navy 2018) is based on an assumed power output of 32 MJ for the EMRG. Because the EMRG is still in the early stages of system design, it is worthwhile to develop cost estimates for EMRGs with alternative power to support trade-off analysis. This is accomplished by using scaling factors, based on the weight in metric tons (MT) of alternative EMRG prototypes. Currently, both 10 MJ and 20 MJ EMRGs have been proposed, weighing 150 MT and 275 MT, respectively. Using the 300 MT weight of the 32 MJ EMRG as a baseline and a linear relationship between cost and weight, scaled cost estimates of $67.33M and $123.44M for the 10 MJ and 20 MJ EMRG are proposed. As with the integration factor assessment, these estimates are necessarily sensitive to underlying assumptions. In this case, rejection of the assumption of a linear relationship between cost would necessarily alter each estimate.

4.1.5 Cost Estimate Sensitivity Analysis

A sensitivity analysis is conducted to allow for potential changes to the integration factors used to calculate the EMRG cost. Figure 2 presents iso-costs for multiple EMRG variants.

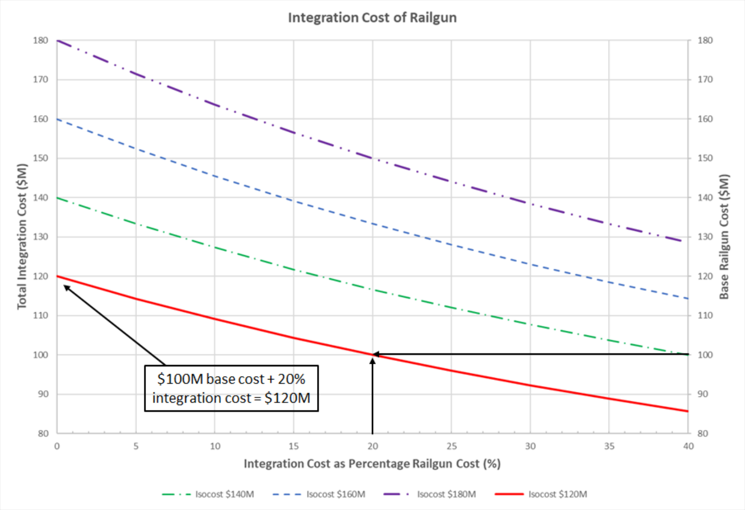


Figure 2: Total Integration Cost for EMRG.

Figure 2 shows base costs on the secondary (right hand side) y-axis, integration costs on the x-axis, and the associated total integration cost (defined as baseline cost plus integration cost) on the primary (left hand side) y-axis for each EMRG variant. As mentioned, the assessment of historical systems suggests that the cost estimate is feasible but also represents the lower range of integration costs. Figure 2 highlights the potential impact of changes to both the integration or baseline costs that may arise from material cost, labor costs, test and evalation, or integration.

5 OPERATIONAL ANALYSIS

Given the wide distribution of potential costs for the EMRG and the large differences between in costs of alternative EMRG variants shown in Figure 2, an operational analysis was conducted to quantify the impact that the EMRG may have in different ARGs. Note that this approach modifies the composition of the ARG, which results in several ship combinations that differ slightly from the traditional definition of an ARG. This is done consistent with the analysis approach for operational missions presented in (Beery and Paulo 2019) where specific system or operational concept characteristics are varied to assess the impact of new system designs. This change specifically accounts for the increased offensive capability that an LPD equipped with an EMRG may provide and these slight alterations do not impact the operational viability of the proposed ARG configurations. An initial version of the operational simulation, developed in the discrete event simulation program ExtendSim and described in (Ciron et al 2020), modeled an ARG comprised of three amphibious ships supplemented by one Arleigh Burke class DDG conducting amphibious assault. The primary focus of the model is the ability of the ARG to simultaneously conduct Anti-Air Warfare (AAW) and Naval Surface Fire Support (NSFS). The defensive nature of AAW and the offensive nature of NSFS creates a competition for resources and constitutes an opportunity for the EMRG to enhance the overall operational effectiveness of the ARG. The model assumes that the ARG maintains a distance of approximately 60 nm from shore, with a move to 15 nm to deploy surface assets during a three phased operation. Phase 1 involves shaping of the battlespace and landing site preparation, Phase 2 involves launching of amphibious assault forces aboard Landing Craft Air Cushion (LCAC) and MV-22 Ospreys, and Phase 3 involves landing force offensive operations. Throughout each phase the ARG ships are required to support both AAW and NSFS, with the operational emphasis shifting gradually from AAW to NSFS throughout the model. Three versions of the model are developed corresponding to low, medium, and high enemy concentration. This is done to assess potential variabilities in the impact of an EMRG equipped LPD across operational scenarios. Low enemy concentration requires the ARG and landing force to disable 5 hardened targets, the medium enemy concentration requires the ARG to disable 10 hardened targets, and the high enemy concentration requires the ARG to disable 15 hardened targets.

This model was adapted to support a cost-effectiveness analysis for the EMRG. That analysis requires definition of alternative ARG configurations, assessment of the ARG configuration that best utilizes the EMRG, and an assessment of the characteristics of the EMRG that have the largest impact on operational effectiveness in that preferred ARG configuration.

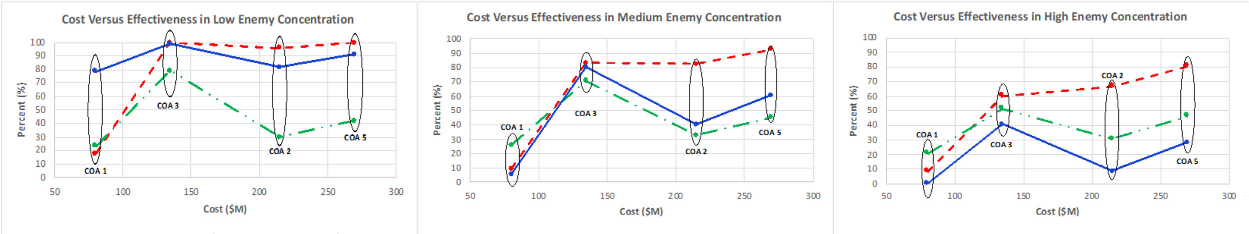
5.1 Amphibious Readiness Group Composition

Using the general ARG structure presented in Figure 1, four alternative ARG configurations are proposed. A baseline configuration (ARG#1) does not utilize an EMRG and is comprised of one LPD, one LSD, one LHD, and one DDG. A second configuration (ARG#2) adds an EMRG to the LPD class ship. A third configuration (ARG#3) removes the DDG and utilizes an EMRG aboard an LPD to provide all AAW and NSFS. A fourth configuration (ARG#4) replaces the DDG from the baseline configuration with a second LPD equipped with an EMRG. In summary, ARG#1 represents a typical ARG structure, ARG#2 adds the EMRG to ARG#1 with no other modifications to the traditional ARG structure, ARG#3 removes the DDG and thereby isolates the EMRG equipped LPD as the sole asset for NSFS and AAW, and ARG#4 explores the potential for the EMRG to replace the NSFS and AAW capabilities of a DDG by replacing the DDG with an EMRG equipped LPD.

To assess the operational effectiveness of the alternative ARG configurations three measures of effectiveness are developed. The first measure, "Percentage of Targets Destroyed" captures the ability of the ARG perform NSFS. To highlight the performance of the ARG specifically focused on AAW a second measure, "Percentage of Enemy Missiles Destroyed" is utilized. An additional measure, "Percentage of ARG Ships Destroyed" is calculated and monitored to ensure survivability is balanced with both AAW and NSFS performance.

5.2 Amphibious Readiness Group Configuration Assessment

Each of the four ARG configurations are examined using ExtendSim. A 512 design point experimental design, presented in (Vieira et al. 2013) is used to examine multiple ARG characteristics such as standoff distance and support distance. Each design point is replicated 30 times to account for the stochastic nature of the simulation model. This resulted in a total of 15,360 simulation runs per ARG configuration. The average performance for each ARG is shown in Figure 3.



			Low Enemy Concentration			Medium Enemy Concentration			High Enemy Concentration		
ARG #	Cost Driver	Cost (FY20$M)	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived
1	DDG	80.12	17.76	23.49	78.75	9.60	26.22	5.75	8.61	20.90	0
2	LPD-E & DDG	134.66	99.72	78.91	98.75	83.09	70.67	80.00	60.21	51.37	40.75
3	LPD-E	214.78	96.05	29.78	81.50	82.32	32.96	40.25	66.69	30.58	8.75
4	2 LPD-Es	269.32	99.75	41.96	91.25	92.47	45.14	60.50	80.54	46.55	28.50

Figure 3: Cost vs. Effectiveness by ARG Configuration

ARG 1 has the poorest performance and ARG 3 has the best performance across all enemy concentrations; however, it is important to distinguish effectiveness from cost effectiveness. Initial observations may trigger leadership to suggest scrapping the DDG and its 5-inch gun due to poor performance, but cost must be considered when reallocating millions of dollars in a defense budget. Assessment of each enemy concentration suggests that the preferred configuration among the ARGs that utilize the EMRG is ARG#3.

By using the cost metrics and performance marks, a scoring system (i.e., "bang for buck") can be developed to compare each ARG and determine which one is the most cost effective. To calculate the cost effectiveness scores, each MOP percentage is equally weighted, added together, and their sum is divided by the cost for that ARG. The scores for each ARG are compiled in Table 7. Observations indicate:

- ARG 3 is the most cost-effective option across all enemy concentrations. It is more cost effective by a factor of 2–3 in medium and high enemy concentrations, when the system is under the most stress.
- ARG 1, which has no railgun, is more cost effective in low enemy concentration than ARG 2 and ARG 4, both of which have railguns.
- ARG 2 and ARG 4 are more cost effective than ARG 1 in medium and high enemy concentrations (high stress on system).

From an operational perspective, the DDG being replaced with one railgun equipped LPD within the ARG results in a higher rate of mission success. Although it may seem intuitive to think that more firepower equates to more targets destroyed, that has proven to not be true in this situation. With respect to ARG 3, the benefits of integrating a RGWS onto LPD-17 are two-fold. The estimated cost of the RGWS is FY20 $45M more than the in-service 5-inch gun, but it is substantially more cost effective, and the now displaced DDG can be utilized by commanders to carry out other missions, conduct additional training, or enter port for necessary repairs.

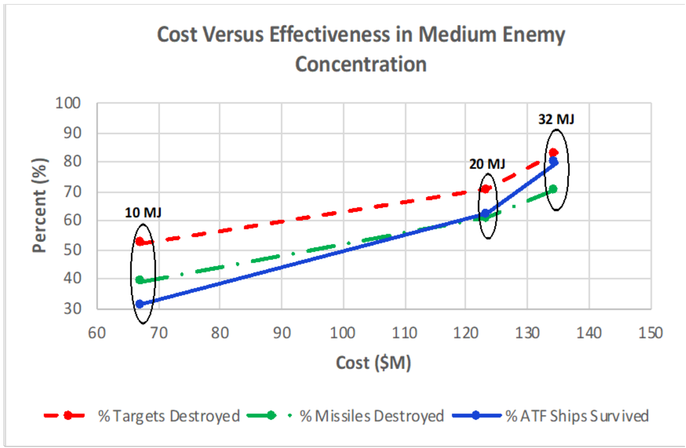
6 EMRG COST EFFECTIVENESS ANALYSIS

In order to gain more detailed insights into the impact that design changes to the EMRG may have on the future operational force, the ExtendSim model was reexamined using variant EMRGs. Because ARG 3 was determined to be the most cost effective across all enemy concentrations in the previous section, this analysis only explores that ARG in one scenario (medium enemy concentration).

Cycle time, projectile velocity, and range are directly related to railgun power output, making them the first properties subject to changes between variants. Although there is no operational or test data for the EMRG due to maturity in the railgun program, the probability of hit for various targets and missiles were slightly reduced within the model to represent the anticipated impact of changes to power output. In each run, the cycle time of the railgun is a randomized using a uniform distribution between the minimum and maximum values in Table 3. The probability of hit values are varied using a five-factor, two-level design of experiment (DOE). To account for the stochastic nature of the model 16 replications of each design point are simulated. Table 3 presents a summary of the design configurations and Figure 4 shows a consolidated set of model results.

Table 3: EMRG Design Characteristics in ExtendSim Model

	EMRG Properties (10 MJ)		**EMRG Properties (20 MJ)**		**EMRG Properties (32 MJ)**	
Variable	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Cycle Time (sec)	9	12	6	9	3	6
Range (nm)	15	75	15	85	15	100
Velocity (Mach)	3.6	3.6	5.8	5.8	5.8	7.3
P-Hit Aircraft	0.4	0.75	0.4	0.85	0.4	0.9
P-Hit Ground Targets - Stationary	0.4	0.85	0.4	0.9	0.4	0.98
P-Hit Ground Targets - Mobile	0.4	0.75	0.4	0.85	0.4	0.9
P-Hit Missiles	0.4	0.7	0.4	0.75	0.4	0.8



Railgun Variant	Cost ($M)	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived
10 MJ	67.33	52.57	39.23	31.25
20 MJ	123.44	70.66	61.15	62.50
32 MJ	134.66	83.09	70.67	80.00

Figure 4: Model Results – EMRG Variants

The results shown in Figure 4 highlight the differences in variant railgun performance. The 10 MJ railgun variant performs the poorest among the group and the 32 MJ railgun performs the best. While there is a clear difference in railgun performance, there are also clear differences in variant EMRG cost. Cost effectiveness score are derived from the cost metrics and MOPs. The 10 MJ railgun is the most cost effective (cost effectiveness score of 1.83) followed by the 32 MJ (1.74) and 20 MJ (1.57), respectively. Although the 10 MJ railgun has the lowest performance marks, it has the highest cost effectiveness score because it is substantially lower in cost.

Regression analysis was conducted to determine which design characteristics from Table 3 had the largest impact on operational performance. Across each EMRG variant, the probability of hit for aircraft targets dominated the results. As the enemy concentration increased, the probability of hit for both missiles and ground targets increased in relative importance. In all scenarios the probability of hit variables had a larger impact than either the cycle time or range characteristics of the EMRG. Two disclaimers regarding these findings are relevant. First, operational employment of the EMRG aboard an amphibious ship required the ships to operate inside the maximum range of the EMRG for large portions of the operational scenario. This may have diminished the relative importance of the range of the EMRG. Second, the interaction between the cycle time and the various probabilities of hit was statistically significant at an alpha value of 0.10 for the medium and high enemy concentrations. This suggests that, depending on the expected operational employment of the EMRG, investment in improvements to cycle time may be beneficial if improvement to probability of hit is not possible.

The results of this analysis do not rule out any individual EMRG variant. Simply because a railgun has the lowest cost, highest performance, or best cost effectiveness score does not mean it is the best fit to replace or supplement existing weapon systems. This assessment provides an initial characterization of the trade space between cost and performance, but other factors such as feasibility, ease of integration, and technological advancement may also influence follow on assessments.

7 CONCLUSIONS AND RECOMMENDATIONS

This paper presented a cost estimate for the Navy's railgun prototype and conduct a cost-effectiveness analysis to inform integration of the EMRG into an ARG conducting an amphibious assault. By using a combination of cost estimation methods, a cost model for the 32 MJ railgun was developed. This cost estimate accounts for inflation and includes various life cycle phase system specific integration factors. The estimate developed in this research is FY20 $134.66, but it is subject to change due to variations in developmental and integration costs. The known weights of other railgun prototypes, in metric tons, were used as scaling factors to develop additional cost estimates, which were used to conduct a comparative system level cost effectiveness analysis between railguns.

Operational modeling of integrating the railgun with LPD class ships indicated that an amphibious force that employs an EMRG in lieu of a traditional 5-inch gun may result in improved operational performance. Specifically, in descending order, the cost effectiveness of each railgun is: 10 MJ, 32 MJ, and 20 MJ.

Detailed assessment of changes to EMRG design suggest that improvements to the probability of hit of the EMRG has a greater impact on performance than improvements to either cycle time or engagement range. This provides an opportunity for tradeoffs to be made in the design of the railgun and its projectile in which the power requirements (and size) can be scaled down without negatively impacting effectiveness, provided the probability of hit of the projectiles is not reduced. Note that longer cycle time does equate to less shots down range, which could make it difficult to combat multiple targets at close range. As with traditional projectiles, this limitation may be overcome via additional short range weapon systems dedicated to terminal self-defense. Further, hit probabilities for air targets had a large operational impact when compared to hit probabilities for ground targets, which could possibly allow for changes to the design or employment of the EMRG aboard amphibious ships.

Because the railgun remains in the early stages of development, there is room for improvement and advancement of the research conducted in this analysis. Assumptions regarding the ExtendSim model were discussed with stakeholders and military experts but it is important to note that they are highly speculative due to the limitations in railgun technology maturation. Fine tuning and continuous updating of the model will result in more accurate simulation outputs for cost effectiveness analyses. The cost estimates can also be improved as more data becomes available for use in the other cost estimation methods. Areas to expand this research include: develop additional CONOPS, mission sets, and firing schemes to use as a baseline for additional operational modeling and simulation. In addition, future work could include development of more accurate cost estimates for the EMRG as cost data becomes available for release and more information is known regarding construction, materials, integration process, and testing. Finally, exploration of integration into other military platforms could prove fruitful.

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