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EXECUTIVE SUMMARY REPORT
ALTERNATIVE PROPULSION METHODS
FOR SURFACE COMBATANTS AND AMPHIBIOUS WARFARE SHIPS
NAVAL SEA SYSTEMS COMMAND

Overview

Requirement

- Section 130 of the FY06 NDAA required a SECNAV report on alternative propulsion methods, (Reference (a)). Report due on January 15, 2007.

Background

- This report builds on the CNO Guidance 2005-068 Study (Reference (b)).
- The scope of the study includes current and future technologies, propulsion alternative life-cycle cost comparisons, operational effectiveness, and "break even" cost for nuclear versus fossil fuel.
- The process and assumptions are documented in the report.

Summary Results

- Ship displacement is not a good predictor for determining power and propulsion systems. Energy demand, both lifetime and peak, drive the answer for power and propulsion systems.
- Operational Tempo and Operating Profile significantly impact the break even analysis of nuclear versus fossil fuel architectures. The range of tempos/profiles used reflect normal peacetime operations plus zero MCOs, plus one MCO, or plus two MCOs in a seven year period.
- Nuclear ship alternatives have higher SCN costs (5^{th} ship ~$600M -$800M premium) but savings exist in O&MN.
- Life-cycle cost break even analysis ($70/BBL - $225/BBL) for Medium Surface Combatants indicates that nuclear power should be considered for near term applications DESC charge to USN is $74.15/BBL crude equivalent.
- Life-cycle cost break even analysis for Small Surface Combatants ($210/BBL - $670/BBL) and Amphibious Warfare Ships ($210/BBL - $290/BBL) suggest nuclear power is not fiscally attractive for near term applications.
- Alternative fossil fuel power and propulsion architectures can provide reduction in life-cycle cost over current all gas turbine plant architectures.
- Ship vulnerability performance can be significantly improved with architecture improvements associated with zonal distribution, integrated power systems, and longitudinally separated propulsors.
- The amount of fuel required for transit and on-station operations can be reduced with use of more efficient propulsors, drag reduction, high efficiency prime movers and combined plants with boost prime movers.

Introduction

The report to congress (RTC, Reference (a)) is written in response to Section 130 of the fiscal year 2006 National Defense Authorization Act (Reference (c)) that directs the Navy to evaluate alternative propulsion methods for surface combatants and amphibious warfare ships. The current fleet's usage of fossil fuel (~20 million barrels per year) for ships represents 8% of DoD (and 0.15% of US) annual usage. The current nuclear fleet provides a fossil fuel use avoidance of ~11 million barrels per year.

The RTC builds upon a study conducted in FY 2005 (Reference (b)), and addresses technologies such as nuclear power, gas turbines, diesel engines, mechanical power transmission systems, hybrid power transmission systems, integrated power transmission systems, combined power plants (e.g., diesel and gas turbine), and various propulsor systems. It identifies aspects of these technologies that are anticipated to mature for transition to ship acquisition programs within the next ten to twenty years. The report compares the performance of alternate power and propulsion systems and associated architectures in non-program-of-record small (~7,500 to ~12,000 metric tons) and medium (~21,000 to ~26,000-metric tons) surface combatants and in amphibious warfare (~34,000 to ~38,000-metric tons) ship concept designs. The study process consists of project elements executed in sequence to provide a response to public law directed products:

- Survey of current and future technology
- Cost versus operational effectiveness
- Break even costs of nuclear and fossil fuel plants

The study evaluated twenty-three different ship concepts with varying propulsion and power systems. These concepts are variants of the three ship baselines: small combatant, medium combatant, and Amphibious Warfare Ship. Mission systems for the ship concepts are similar to current or projected systems.

Conclusions

- Mission and operating requirements drive the need for particular power and propulsion system architectures, not ship displacement.
- Acquisition Cost Premiums for nuclear power are (5^{th} ship between two shipyards):
  - Small Surface Combatants: ~ 80% (~$600M)
  - Medium Surface Combatants ~ 22% ($600-$700M)
  - Amphibious Warfare Ships ~ 46% (~$800M)
- Based on the fuel usage projections inherent in this study, the break even costs per barrel of fossil fuel at which nuclear propulsion becomes economical for the various options are:
  - Small Surface Combatants: $210/BBL to $670/BBL
  - Medium Surface Combatants:$70/BBL to $225/BBL
  - Amphibious Warfare Ships: $210/BBL to $290/BBL
- Ship vulnerability can be reduced by the employment of redundancy, zonal distribution, longitudinal separation of prime movers and propulsors (e.g., auxiliary propulsor units) and use of flexible energy conversion (e.g., integrated propulsion systems) of power and propulsion systems.
- The number of refuelings (independent of other stores replenishments) and the amount of fuel required by ships surging to theater is reduced by efficient energy conversion systems and high energy densities. The most effective

means to achieve this operational effectiveness advantage are:

- o Nuclear energy.
- o Propulsor systems that maximize propulsor efficiency and reduce drag by minimizing the number of shafts/screws, or in the future, incorporating podded propulsors and/or low drag hull forms.
- o Plant architectures matched to operational requirements.
- o Large fuel tankage capacities.

- Sustainability, measured by time on station and low speed operations, is enhanced by energy efficient plant architectures. The most effective architectures include:
  - o Nuclear energy.
  - o Diesel engines and generators alone or in combined power plants with boost gas turbine prime movers if high speed is also a requirement. (Fuel cells could provide similar benefits if the technology matures.)
  - o Integrated power and propulsion systems.
- Nuclear propulsion systems are technically feasible for small and medium combatants and for amphibious ships using existing reactor designs. The scope of this study did not include costs or time required to re-establish a nuclear surface ship construction capability. Likewise, this study did not include beneficial impacts to the nuclear industrial base from increased surface ship workload.
- Nuclear propulsion options provide operational advantages in surge to theater and time on station for all variants studied. These operational advantages are even more pronounced for scenarios of high energy demand over long durations in tactical situations (e.g., high-power radars, high speeds, and electric weapons and sensors). Trends in ship weapons and sensors toward significantly higher power and energy demands will further highlight these advantages.
- Significant growth in electrical power loads to support future sensors and weapons will be required to address projected threats and will have major impacts on ship power and propulsion architectures and fuel requirements. This will require a more detailed understanding of future operational requirements to better inform the selection of power and propulsion architectures and components. As energy requirements increase, the value of energy efficient next generation systems increases.

Recommendations

- The Navy should continue to use the methods and processes developed for this study in analysis for future ships to evaluate the operational effectiveness of propulsion and power systems. Future studies should include quantifiable analyses of ship vulnerability, sustainability, and timeliness that can be evaluated against acquisition and life-cycle cost.
- The Navy should consider ship options with nuclear power and combined plant architectures (e.g., diesels combined with gas turbine boost) in studies for future ships performing missions assigned to surface combatants and amphibious warfare ships.
- The Navy should continue to invest in RDT&E efforts toward increasing power density, improving affordability, and improving energy efficiency of Naval ship power generation (e.g., fuel cells), power distribution, propulsion transmissions, and technologies to reduce hull drag.
- The Navy should invest in RDT&E for propulsors providing improved efficiency and increased longitudinal separation.

Technology

Two energy sources are considered: diesel fuel marine and nuclear. A wide range of technologies at varying levels of maturity are evaluated in the RTC; only technologies that are available for integration into ships that would join the fleet in the 2017 to 2027 timeframe are considered in the supporting studies.

The following table summarizes current power and propulsion architectures and technologies that have been incorporated in recently designed surface combatants and amphibious warfare ships.

Ship	Energy Management Systems				
	Storage	Conversion	Distribution	Transmission	Thrust Generation
DDG-51	Fossil Fuel (DFM/F76)	Gas Turbine	Segregated Electric	Mechanical COGAG	Controllable Pitch Propeller
LHD-8 / LHA-6		Diesel Cruise / Gas Turbine Boost		CODLAG	
LPD-17		Diesel		Mechanical CODAD	Controllable Pitch Propeller
LCS (LM)		Diesel Cruise / Gas Turbine Boost		Mechanical CODAG	Waterjet
LCS (GD)					
DDG-1000		Gas Turbine	Integrated Electric	Electric Motor	Fixed Pitch Propeller

COGAG: Combined Gas Turbine and Gas Turbine Power Plant
CODAG: Combined Diesel and Gas Turbine Power Plant
COLAG: Combined Diesel Electric and Gas Turbine Power Plant

The Navy and industry are investing in propulsion technologies that offer the potential to improve future naval ship designs. The following table lists power and propulsion plant architectures that should or are being considered for ships in design or construction (Next Navy) and for future ships (Navy after Next).

	Next Navy (Ships in Design and Construction)	Navy after Next (Future Ship Designs)
Small Surface Combatant	LCS – Combined Gas Turbine and Diesel Mechanical Propulsion with Diesel Generator Sets	Combined Gas Turbine and Diesel Plants
		Single shaft with longitudinally separated secondary propulsion unit.
		IPS for ships with high mission system electrical loads.
		Fuel Cells
		Nuclear Power
Medium Surface Combatant	DDG-1000 – Gas Turbine-Electric Integrated Power System	IPS for ships with high mission system electrical loads and ships requiring high levels of survivability.
		Longitudinally separated Secondary Propulsion Unit.
		Fuel Cells
		Combined Diesel and Gas Turbine plants.
		Nuclear Power
Amphibious Warfare	LHD-8, LHA-6 – Hybrid Gas Turbine Mechanical and Diesel Electric	IPS or Hybrid Plants
		Longitudinally separated Secondary Propulsion Unit.
		Fuel Cells
		Nuclear Power

The goals of the current and planned technology development efforts are to improve affordability, power density, efficiency, and satisfy the energy demands of future mission systems.

Energy Requirements

Ships evaluated in the RTC are non-program-of-record ship concept designs, with capabilities bounded by the Navy's 2006 30-Year Shipbuilding Plan. Warfare mission capabilities, and therefore power loads, are kept constant across all variants in each class but are reflective of the warfare capabilities of the ships envisioned in the 30-Year Shipbuilding Plan. Thus, the ships of this study are considered ‘energy management system surrogates’ of the ships in the 30-Year Shipbuilding Plan.

Official Defense Planning Scenarios (DPS) (Baseline Security Posture and MCO’s) are used to define the quantities and capabilities of the 313 ship future fleet are also used to develop the warfare and mobility system energy requirements and operating tempos for the ships modeled.

The energy demand signal is derived from the speed range in given warfare system energy usage states for each ship over its expected lifetime. Each variant is exercised in energy usage states to determine propulsion and electrical power demands. An analytical model determines the lifetime energy demand based on the energy requirements and expected plant line-ups.

The RTC assumes a one-to-one relationship between nuclear and fossil fuel ships to sustain a notional force structure. The RTC does not make any assumptions regarding the affordability of alternative propulsion ships as it relates to either a notional $13.4B per year (FY05$) shipbuilding plan, or total costs to achieve the Navy’s 313 ship fleet.

Cost

Fifth ship (using two shipyards) acquisition cost and life-cycle costs are estimated for each ship baseline and associated variants. Due to the maturity of power and propulsion system equipment, when possible, acquisition costs include actual cost return data or vendor quotes for power and propulsion system material.

Nuclear ship acquisition prices reflect reactor cores that last for the life of the ship. Conventionally powered ship life-cycle operations and support costs reflect the price of DFM/F76 as delivered at sea.

Non-recurring costs are not specified as they are dependent on capability growth (both military and industrial) and acquisition strategies which are outside the scope of this study. Non-recurring costs are not expected to be a major life-cycle cost discriminator among propulsion options.

Life-cycle costs are expressed in FY2007 dollars. Cost estimates assume that ships would be built at shipyards that normally produce non-nuclear warships, except that the single subdivision enclosing the nuclear primary plant would be built at a shipyard already licensed and qualified to build nuclear ships. Any cost inefficiencies incurred by building portions of the ship at two sites are not included. Likewise, the beneficial cost impacts to the nuclear industrial base due to increased workload are not included.

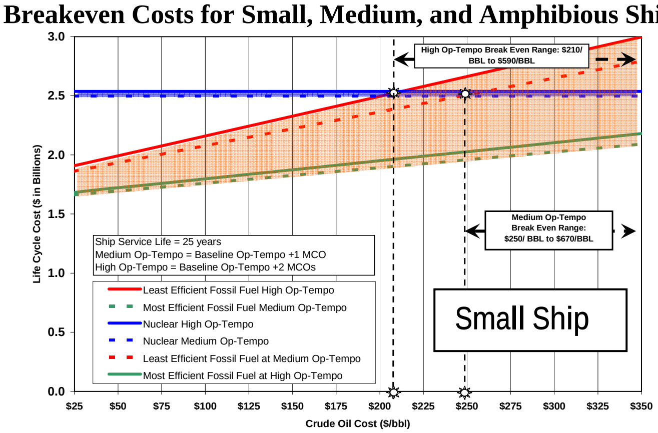
The breakeven analysis of the study is performed in constant FY 2007 dollars. Since the scope of the study does not assess the build quantity, the development cost of non-propulsion technologies, the beneficial impacts to the nuclear industrial base, nor the costs and time required to adjust a nuclear surface ship construction capability, the results presented herein indicate conditions where nuclear propulsion could be considered a viable alternative in future analyses. More detailed review would be required for specific tradeoffs.

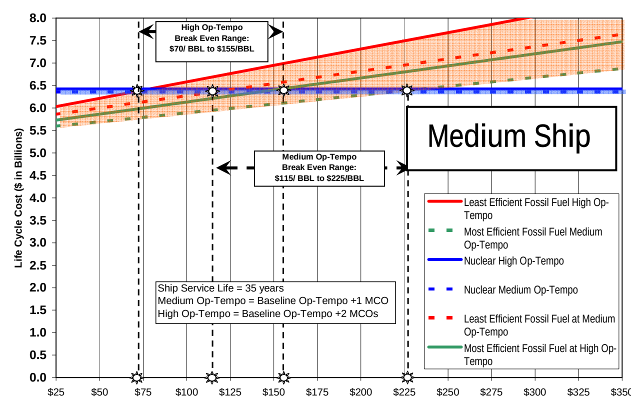
The life-cycle cost estimates incorporate the following costs: inactivation, defueling (nuclear variants only), disposal, burdened fuel costs, manpower costs, and maintenance. The baseline market price of fuel used in this analysis is $74.15/BBL of crude oil, and its burdening buildup results in a delivered cost of DFM F76 of $152.95/BBL.

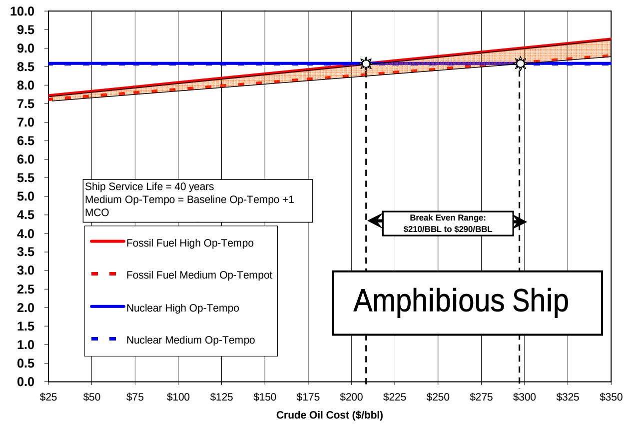
Break even regions are defined for the high (baseline plus two MCOs) and medium (baseline plus one MCO) operational tempos. Analyses correlate historic and Defense Planning Scenario derived steaming hours underway over the period from FY2000 through FY2006. The demands for each of the ship types during this period strongly correlate with the medium operational tempo (baseline plus one MCO) excepting the addition of the FY2002 lesser contingency, thus validating OpTempo profiles applied to breakeven life-cycle costs.

The range of breakeven costs for each ship concept are driven by both OpTempo and propulsion plant efficiencies. The higher OpTempo includes two MCOs in a seven-year period, a likely stressing scenario outside of historical precedent. Therefore, the lower breakeven costs are less likely to be realized if historic trends continue. The more likely range of breakeven costs based on historical precedent are bounded by the one MCO, medium OpTempo. For example, while the medium surface combatant breakeven range is $70/BBL - $225/BBL, the more likely range is $115/ BBL - $225/ BBL based on historical precedent.

Breakeven Costs for Small, Medium, and Amphibious Ships







Operational Effectiveness Analysis

The operational effectiveness of each ship concept is evaluated in terms of mobility, survivability, and warfare effectiveness in the context of operational scenarios and includes attributes such as timeliness, percent mission complete, and sustainability. Operational Presence is evaluated as the time a ship variant can remain on station while conducting missions in theater. DoD Defense Planning Scenarios provided the basis for the speed time profile and ship service electric loads modeled in the Operational Presence analysis. Battle loads (Condition 1) were modeled in-theater and summer cruising loads with radars on (Condition 3) were modeled in transit to and from the Sea Base refueling point.

The nuclear powered variants are superior to fossil fuel powered variants in providing operational presence on station limited only by ship stores capacity. Fossil fuel plant variants provide between 89% and 95% of the nuclear powered plant operational presence for small surface combatants and between 87% and 90% of the medium nuclear powered surface combatant. Fossil fuel plant variants with diesel prime movers have a significant advantage over gas turbine variants. The best performing fossil fuel variant is SFH-3, the fossil fuel mechanical-electric drive single shaft hybrid variant. This variant best captures the system efficiencies and flexibility provided by an IPS system.

Similar improvements in operational presence can be expected by employing hybrid IPS architectures. The hybrid architecture was not modeled in the other fossil fuel baselines (MFM-1 and AFM-1). Again, increased fuel tankage could be pursued to improve fossil fuel variants operational presence at increased acquisition and LCC.

For the purposes of this study, Surge to Theater was evaluated in two ways:

1) In terms of the number of refuelings and the amount of fuel required to reach a theater of operations from a homeport at maximum surge speeds of 30 knots for Small and Medium Surface Combatants and 25 knots for Amphibious Warfare Ships.

2) The best speed attainable for those ships without refueling.

Systems that provide high-energy storage capacity and density, high energy conversion (i.e. engine) efficiencies and high thrust generation (i.e. propulsor) efficiencies improve the performance against the nuclear powered benchmark.

Of great significance are the numbers of propulsion architectures that provide more operational flexibility than the pure gas turbine architecture, which is the architecture in the fleet today. It should also be noted that this analysis assumed that ships refueled when they had burned 50% of the fuel in their tanks. The fleet is more conservative than this, which would only drive up the number of underway replenishments, and hence increase the demands on oiler infrastructure.

Nuclear powered ships are superior to all fossil fuel variants in the transit scenarios modeled as non-nuclear surface combatants required between 2-3 refuelings to support a surge from CONUS to the Mediterranean Sea. Other technologies providing high levels of performance relative to the mission timeliness metric are diesel prime movers and single screw propulsors.

Vulnerability is evaluated as the probability of losing mission capability following damage from threat weapons. This analysis purposely looked at the ability of the various options to sustain hits. The primary focus of this analysis was the Small Surface Combatant, because the smaller size of the platform is likely to exacerbate those stressors that drive vulnerability successes or failures. In all, 12 variants were evaluated for the Small Surface Combatant.

Results of ship vulnerability assessment studies suggest that power and propulsion systems and architectures reduce ship vulnerability through:

- Redundancy
- Zonal distribution systems (vertical and longitudinal alignment between energy sources and loads)
- Separated distribution of propulsion systems (Auxiliary or Secondary propulsors located at the forward end of the ship)
- Flexible energy conversion systems (electric or steam integrated power systems) providing for distributed conversion architectures.

References

(a) NAVSEA Concept Study Report, Report to Congress on Alternative Propulsion Methods for Surface Combatants and Amphibious Warfare Ships, Webster, James S., Jan 2007.

(b) NAVSEA Concept Study Report, CNOG 2005-068 Sea Basing: Alternate Propulsion For Submarines and Surface Combatants, Webster, James S., Ser 05D/062, Mar 2006 (NOFORN).

(c) FY06 National Defense Authorization Act, House Resolution 109-360, section 130.