INVITED PAPER

History and the Status of Electric Ship Propulsion, Integrated Power Systems, and Future Trends in the U.S. Navy

This paper describes the history and the present status of electric propulsion and the integrated power system (IPS) approaches and ship classes developed by the U.S. Navy, from the early 1900s through today.

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ABSTRACT | While electric propulsion for warships has existed for nearly a century, it has only been since the end of the Cold War that modern integrated power systems have been developed and implemented on U.S. Navy warships. The principal enablers have been the products of research and development for rotating machines (generators and propulsion motors), power electronics (power conversion and motor drives), energy storage, and controls. The U.S. Navy has implemented this advanced technology incrementally. Notably, DDG 1000 with its integrated propulsion system and CVN 78 with its electromagnetic aircraft launch system will soon join the fleet and mark another important advance to the electric warship. In the future, the integration of electric weapons such as railguns, high power radars, and lasers will result in the final achievement of the electric warship.

KEYWORDS | Defense industry; electric machines; intelligent control; marine vehicles; research and development

I. INTRODUCTION

The end of the Cold War marked the beginning of a multidecade evolution of the surface combatant into the electric warship. In 1989, the concept of "technology clusters" emerged to advocate the synergistic research and development of surface combatant technology [11]. Technology clusters promised to enable concurrent systems engineering and component R&D, provide programmatic stability, and decrease fleet introduction time. The foundational "cluster A" consisted of integrated electric drive, advanced propulsor system, intercooled recuperated (ICR) gas turbine, integrated electrical distribution system with pulse power, machinery monitoring and control, advanced auxiliary system, and low observability/loiter power system. Cluster A enabled the introduction of other clusters, most notably, cluster E, electromagnetic pulse power. Over the next several decades, the U.S. Navy matured these technologies and incrementally introduced them into ship designs; the culmination will be the upcoming delivery to the U.S. Navy of the first modern electric warship featuring an integrated power system (IPS) *U.S.S. Zumwalt* (DDG 1000). Modern electric power technology has also been introduced into auxiliary ships (T-AKE 1 class and MLP 1 class), amphibious warship ships (LPD 17 class, LHD 8 and LHA 6 class), aircraft carriers, submarines, and DDG 51 flight upgrades. Furthermore, directed energy weapon prototypes such as the laser weapon system (LaWS) are beginning to be fielded, and the electromagnetic railgun is currently transitioning from an early electromagnetic launcher prototype into a weapon system technology development program. High power radars, such as the air and missile defense radar (AMDR), have also been enabled by increased electric power availability from electric warship technology. While the term "technology cluster" is no longer widely used, the

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concepts it represents continue to influence technology development.

II. NAVAL ELECTRIC PROPULSION

A number of papers have provided in-depth discussions of the use of electric propulsion in naval ships from the early 1900s through World War II. However, it was not until the 1960s that serious efforts were initiated to develop advanced machines with higher power densities that could be used to provide propulsion on small and medium size surface combatants (such as frigates, destroyers, and cruisers) and on submarines. These early efforts focused on the use of low-temperature superconductivity to provide high magnetic field strengths that would lead to more compact machines. The technology chosen was direct current (dc) homopolar for several reasons, but mainly because the homopolar motor, requiring no commutation, is a pure dc machine that is extremely quiet. There were, however, two drawbacks: the first was that homopolar machines are low-voltage, high-current devices that can require up to 60 000 A at full scale; and the second was that low-temperature superconductors operate at liquid helium, or near-liquid helium temperatures, thus requiring complex cryogenic systems.

To accommodate the very high currents, early machines used liquid metal current collectors, a sodium–potassium eutectic, that had to be kept in an inert atmosphere thus requiring complex rotating seals. To reduce the current densities, heteropole and hexapole rather than dipole configurations were attempted. These did succeed in increasing machine voltage somewhat, but current densities were still high. In an attempt to eliminate the need for liquid metals, solid brushes were also attempted, but the large number of these and their relatively short lifetimes made them less than satisfactory. One advancement that did provide improvement in simplicity was the development of niobium–titanium in place of niobium–tin that could be operated in the range of 10° K vice the 4° K requirement for the niobium–tin. This enabled elimination of the helium liquefier that was complex and too fragile for shipboard application. Ultimately, the homopolar technology was abandoned in favor of alternating current (ac) machines that can be provided in the sizes required for ship propulsion without the complexities of the dc homopolar system.

In an attempt to use conventional synchronous machines rather than the superconducting machines, the U.S. Navy established the Integrated Electric Drive (IED) program. Recognizing that direct drive motors would be difficult to incorporate in destroyer-sized ships, high-speed machines were selected that were completely liquid cooled, both rotor and stator, with epicyclic reduction gears on the output shafts to reduce the speed to that required by the fixed pitch propellers. To reduce both the size as well as the efficiency penalty of motor drives that were available at that time, part range frequency changers were employed that were used for maneuvering and low-speed operation. At higher speeds, the identical generators and motors operated synchronously, which provided both quiet and efficient powering. This system, although relatively compact and quiet, was still only a propulsion system that was both less efficient and more costly than the mechanical transmission that it replaced. It was not until the evolution of the IPS that the full potential of electric ship technology could be realized. By fully integrating all ships' power sources and loads to operate efficiently under all conditions and to provide margins for future growth the IPS provided a significant improvement in operational effectiveness.

III. INTEGRATED POWER SYSTEM

A number of studies and projects in electrical propulsion and electrical power system technology were conducted in the 1960s and 1970s and formed a solid base of knowledge. The specific efforts leading to incorporating IPS on DDG 1000 can be traced back to November 1979 with a series of studies under the Advanced Integrated Electric Propulsion Plant Conceptual Design (AIEPP) project managed by the Naval Sea Systems Command (NAVSEA) [10]. During the early 1980s, the U.S. Navy began the design of DDGX (future DDG 51 class). Heavily influenced by AIEPP, electric drive was chosen as the baseline propulsion system during the DDGX preliminary design. This decision, however, was reversed in contract design due to concerns over cost and schedule risk as well as a perceived lack of expertise within the Navy and industry design and engineering workforce. As a result, the traditional mechanical drive plant used in the DD 963 and CG 47 class was employed in the DDG 51 class.

In September 1988, Chief of Naval Operations Adm. Krolick and Graham stated in a speech to the Navy League [11]:

> Integrated electric drive, with its associated cluster of technologies, will be the method of propulsion for the next class of surface battle-force combatants, and I am directing all the major Navy organizations involved in these efforts to concentrate their energies toward that objective.

Aligned with this declaration, the previously described IED program emerged to develop a very quiet and power dense electric propulsion system for a future surface combatant. General Electric Co. was awarded a contract to develop prototype hardware in November 1988. This hardware included the 120-Hz, six-phase, 4160-V, 25-khp 3600-rpm very quiet rotating machine that could serve as either a generator or as a geared propulsion motor.

The Soviet Union collapsed between 1989 and 1991. The subsequent end of the Cold War witnessed a shifting of the nation's priorities toward a "peace dividend" rather than continued defense spending. With the DDG 51 class just being introduced, the Navy could no longer afford to develop a future surface combatant. The IED program was developing an expensive technology that did not have a transition path to a ship design. In 1991, the IED program came under the Advanced Surface Machinery Programs (ASMP).

ASMP engineers expended considerable effort in fall 1991 and spring 1992 to reduce the cost of the IED system and to take advantage of commercial technology. Reflecting the new austere fiscal reality, Captain Graham, the program manager, redefined program objectives from increasing military effectiveness at greater cost to making systems more affordable without degrading performance; the ambitious acoustic performance of the IED system would likely not be needed in the coming decades. ASMP engineers discovered that other emerging technologies could produce capable, but more affordable power systems than what was achievable with the IED system. Consequently, ASMP focus shifted away from completing the IED program. Some IED hardware was delivered to the Navy, but never tested.

In 1992, ASMP shifted its focus to defining a power system architecture that was both affordable and suitable for the range of naval ships the Navy planned to acquire. The basic architecture of IPS and the different module types were established as described in [3]:

> The Integrated Power Architecture (IPA) provides the framework for partitioning the equipment and software of IPS into modules. IPA defines six functional elements and the power, control and information relationships between them. Every IPS module corresponds to one of the IPA functional elements. A power relationship is one involving the transfer of electrical power between two functional elements. A control relationship refers to the transmission of commands from one functional element to another while an information relationship refers to the transmission of data from one functional element to another. The six functional elements are Power Generation, Power Distribution, Power Conversion, Power Load, Energy Storage and System Control.

The IPS concept in 1992 included generalized modules that would be engineered ahead of their application for a specific ship following an open architecture defined by evolving "baselines." These modules would be described by module characterization sheets which provided the necessary information to integrate them into a system as well as the necessary specifications and standards to procure the modules. An IPS design data sheet would provide the process for developing an IPS configuration by tailoring the individual modules to meet the ship requirements.

The electric power system baselines were intended to ensure that IPS solutions would always exist for new naval ship designs and reflect state-of-the-market technology. If the Navy needed a power-dense, quiet electric drive system in the near term, then ASMP would propose a system based on the IED program. This set of technology was called "baseline 1" and reflected the then current program of record. Since an affordable system for an amphibious warfare ship or auxiliary ship was not possible with "baseline 1," a power system based on militarizing commercial technology would be proposed. This was called "baseline 2." These baselines would be supported by specifications, standards, handbooks, design data sheets, and design tools. Ongoing science and technology (S&T) and research and development (R&D) efforts would eventually require new power system architectures. "Baseline 3" would replace "baseline 1" with a more affordable power system architecture for combatants, and a future "baseline 4" would similarly replace "baseline 2" for amphibious warfare and auxiliary ships. These baselines were an early application of the "product line" approach to technology development [5].

IPS also incorporated provisions for ac zonal distribution system and dc zonal distribution for ship service loads. Flight IIa of the DDG 51 class incorporated a modified version of the ac zonal distribution system (see [22]). AC zonal distribution systems were also incorporated into LPD 17 and LHD 8. The dc zonal distribution system became the integrated fight through power (IFTP) system and transitioned to DDG 1000 as part of IPS. IPS became an electric warship enabler and offered the following opportunities for ship design [4].

1) Support high-power mission systems: All power generated on an electric warship can be made available for ship service needs. The large amount of available power enables many new technology weapon system elements such as high-power radars, electromagnetic guns, electromagnetic launchers, and laser weapons. The availability of high power will result in the weapon systems themselves changing as well as how the weapon systems integrate into the ship. For example, as electric weapons replace conventional guns and missiles, ship systems such as magazines, weapons handling gear, ship safety, and protection systems will also radically change.
2) Reduce number of prime movers: Electric warships enable fewer prime movers to service higher power loads. For example, a conventionally designed LPD 17 has nine rotating machines with the equivalent of 43 MW of total ship power: four medium-speed diesel prime movers for propulsion

along with five diesel generators for electrical power. An IPS-based new design LPD could be configured using only four prime movers. Fewer prime movers may result in better fuel efficiency, reduced acquisition cost, reduced maintenance, and reduced manpower requirements.

3) Improve efficiency of prime movers: Overall system efficiency of an IPS configuration can be higher than for an equivalent mechanical drive design. The overall efficiency of a mechanical drive ship can suffer because the propulsion prime movers are inefficient at low ship speed and generator sets are often lightly loaded. With IPS, ship service and propulsion loads are managed off the same distributed system enabling efficient loading of prime movers.
4) Improve efficiency of propulsors: With an IPS, the propulsion shaft line can be simplified with the removal of the traditional controllable pitch propeller (CPP) system. Alternate technologies such as contra-rotating propellers or pod propulsion are enabled. The improved performance of pod propulsion has been recognized by the builders and operators of merchant ships and is featured in many ferries, cruise ships, and other commercial ships. Contra-rotating propellers can also improve efficiency. Since many propulsion motors feature two independent motors on the same shaft, dedicating each motor to its own propeller does not add significant complexity. Designing long-life bearings to support the inner shaft is an engineering challenge that has been successfully achieved in commercial practice. Alternately, a hull-mounted shaft and propeller can be paired with a pod to provide contra-rotation.
5) Provide general arrangements flexibility: The electric warship enables challenging conventional ship design rules. Traditional ship designs locate prime movers low in the ship to align with the shafts. IPS provides flexibility to locate generator sets in almost any location (subject to stability considerations). The shaft line can be simplified with direct drive motors. Ship designers can also challenge conventional designs associated with the longitudinal separation of propulsors, improve survivability, and improve ship maintainability. IPS enables new approaches to combustion air and exhaust design.
6) Improve ship producibility: By eliminating long shaft lines, shipbuilders can simplify the erection schedule and thereby reduce the ship construction schedule. Through careful arrangement of the generator sets within the ship may enable delaying the in-yard need date for these items, reducing the likelihood that the equipment will be damaged during the ship's construction. Furthermore, each module can be tested before integration into the ship, reducing the risk that equipment will fail during the ship acceptance process. Zonal distribution systems shorten cable lengths and minimize the number of spaces a cable has to penetrate.
7) Facilitate fuel cell integration: Fuel cells promise to improve the fuel efficiency of future naval power systems. Since fuel cells directly produce electrical power, their integration into an electrical power system is natural. Fuel cells are just another type of generator set. While the technical challenges of integrating fuel cells has limited their applications, these challenges are being addressed by the Navy and industry. At some time in the future when fuel cells become viable, the electric warship will facilitate their integration into ship designs.

During 1992, ASMP began discussions with Newport News Shipbuilding and Kamen Electromagnetics to develop a "baseline 3" power system using permanent magnet motor (PMM) technology. This technology promised to provide combatants high-power density at a cost lower than what could be provided by "baseline 1." "Baseline 3" was also intended to be capable of supporting future pulse power weapons such as lasers and railguns. To demonstrate the PMM technology, ASMP established a Reduced Scale Advanced Development (RSAD) project that in 1994 resulted in the successful testing of a 3000-hp PMM scaled as a prototype of a 25 000-hp motor.

In fall 1992, ASMP focused IPS entirely on "baseline 3" since "baseline 1" was unaffordable, and "baseline 2" did not need any further development. Hence, IPS would address the power system needs of the next surface combatant following the DDG 51 class. Auxiliary ships, such as the T-AKE 1 class (and later the MLP 1 class), would use commercial marine IPS solutions, fulfilling the "baseline 2" concept.

In February 1995, NAVSEA awarded an IPS Full Scale Advanced Development (FSAD) contract to Lockheed Martin's ocean, radar, and sensor systems. The FSAD system would serve as a test bed for technologies that could be incorporated in a future shipboard IPS architecture. As the systems integrator, Lockheed Martin was responsible for developing the standards, specifications, design data sheets, and handbooks for designing and integrating an IPS system. Unfortunately, while Lockheed Martin was an outstanding systems engineering organization for developing specific products, it was not a company accustomed to developing a product line. Much effort was expended to transition the knowledge gained in the systems architecting process conducted by the ASMP Government team to enable the contractor to fulfill the envisioned role of IPS systems integrator. The mismatch between the skills of a product line developer and a product developer was not resolved. Following the IPS

FSAD contract, Lockheed Martin ended its involvement with IPS.

In June 1996, an SC-21 (predecessor to the DDX program) IPS Ship Impact Study compared IPS and mechanical transmissions. This study, conducted by the SC 21 Cost and Operational Effectiveness Analysis (COEA) Team, found that the IPS ship cost $10 million less in acquisition, was 400 LT smaller, and consumed 17% less fuel. In March 1998, the SC 21 COEA report by CNA concluded IPS resulted in "Significant reductions in ship design, construction, and life cycle costs."

The integration of IPS into the DD 21 program was described by Walsh [24]:

> In early 1999, senior Navy officials-including Adm. Frank L. Bowman, director of the Navy's nuclear propulsion program, supported by Vice Chief of Naval Operations Adm. Donald L. Pilling; Vice Adm. George P. Nanos Jr., NAVSEA commander; Rear Adm. George R. Yount, deputy for engineering in NAVSEA; and Rear Adm. Joseph A. Carnevale Jr., program executive officer for the DD-21-initiated an effort to accelerate Navy electric drive work. In 1998, the IPS program was transferred from NAVSEA's Engineering Directorate to the PEO DD-21 (PMS-500). The fiscal year (FY) 1999 Navy budget provided $33.9 million for IPS, $4 million of which was targeted for the DD-21 Blue and Gold team concept studies. No funding was provided in the FY 2000 budget, however. Navy leaders are considering options for reprogramming funds from other programs for lED work during the year ahead.

In January 2000, the Secretary of the Navy announced that IPS would become part of the DD 21 baseline [1]. One consequence of moving IPS into a ship acquisition program was that the effort became focused solely on this one transition. The product line approach was largely abandoned as focus was placed on producing a product for the DD 21/DDX/DDG 1000. The module boundaries defined in 1992 were redefined into a ship-specific low-voltage power system (LVPS) developed by DRS Technologies and a high-voltage power system (HVPS) developed by Converteam. While a test facility and a working IPS were developed, the vision for an IPS product line was not realized.

Initially, the IPS system for DDG 1000 was based on a PMM. In February 2005, however, delays in testing resulted in the design shifting to the fallback advanced induction motor (AIM) and a 4160-V distribution system to eliminate the need for a propulsion transformer. Subsequent testing in 2008, although too late for integration into DDG 1000, validated that the PMM technology "is a viable alternative for naval ship propulsion applications" [2]. Likewise, an alternate technology full scale superconducting synchronous motor subsequently would also successfully complete testing in 2009 [17].

Advanced power system technologies were introduced into amphibious warfare and auxiliary ships as well. LPD 17, for example, incorporated a zonal ac distribution system. T-AKE 1 introduced a modern commercially-based IPS. LHD 8 introduced hybrid electric drive to the U.S. Navy.

The Gerald R. Ford (CVN 78) class of aircraft carriers is also taking a step toward the electric warship. The electrical capacity for CVN 78 will be 2.5 to 3.0 times as much as for the previous Nimitz Class. Two significant electrical loads are the dual band radar and the electromagnetic aircraft launch system (EMALS) [20]. EMALS replaces the steam catapults of previous carriers. The EMALS system is a multimegawatt system that incorporates advanced power conversion, energy storage, and linear motors [8]. The U.S. Navy is learning much from its integration into the carrier's electric power system.

A. Electric Ships Office

On November 30, 2007, the U.S. Navy established the Electric Ships Office (ESO) and concurrently issued a Next Generation Integrated Power System (NGIPS) Technology Development Roadmap. This roadmap featured three power generation architectures (medium-voltage ac, high-frequency ac, and medium-voltage dc) and a zonal electrical distribution system (ZEDS) architecture based in part on the DDG 1000 Integrated Fight Through Power (IFTP). The NGIPS Technology Development Roadmap defined the state of the technology, defined the need for IPSs, defined the power system architectures, listed technology development needs, and proposed an open-architecture-based business model. It did not define an execution plan.

The NGIPS Technology Development Roadmap influenced S&T initiatives. The Electric Ship Research and Development Consortium (ESRDC) produced many technical papers and theses to explore the different risk areas identified in the roadmap. At the U.S. Office of Naval Research (ONR), the NGIPS S&T efforts (as described on the ONR website) concentrated on topics included in the roadmap:

- advanced naval power systems modeling and simulation'
- high-density energy storage;
- advanced power generation to reduce fuel consumption;
- diagnostics that clearly define the fault severity and accurately locate the fault and prognostic capability that reliably foretells the future condition of the equipment and system;
- advanced power converter topologies;
- application of advanced semiconductors;
- power system control architectures;
- power and energy management methodologies;
- dynamic stability analyses.

Professional societies such as the American Society of Naval Engineers (ASNE), the Society of Naval Architects and Marine Engineers (SNAME), and IEEE provided multiple forums to advance electric warship technologies. A number of conferences and symposiums were held to enable the power system and ship design communities to collaborate and share results.

The increased interest in IPSs also led to a number of standards activities to capture the evolving lessons learned. The first success was the publishing of the IEEE 1662-2008 Standard *IEEE Guide for the Design and Application of Power Electronics in Electric Power Systems on Ships*. The IEEE 1709 Standard *Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships* followed in 2010 and the IEEE 1826 Standard *IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW* was approved in 2012. Updates to the IEEE 45-2002 Standard *Recommended Practice for Electric Installations on Shipboard* are currently being developed.

Within the Navy, design data sheets DDS-200-1 *Calculation of Surface Ship Endurance Fuel Requirements* and DDS 310-1 *Electric Power Load Analysis (EPLA) for Surface Ships* were updated to reflect changes needed due to the introduction of advanced electrical systems. A new DDS 200-2 *Calculation of Surface Ship Annual Energy Usage, Annual Energy Cost, and Fully Burdened Cost of Energy* was approved in 2012. A number of other component specifications and electrical power system military standards were updated.

As time progressed, the ESO increased its portfolio of component development projects. The ESO is currently developing a hybrid electric drive and an energy storage module (ESM) for back fitting on existing DDG 51 class ships to improve fuel efficiency, a new advanced power generation module (APGM) for forward fit on the DDG 51 Flight III, LM2500 efficiency improvements, and an air and missile defense radar (AMDR) power conversion module (PCM) for DDG 51 Flight III. The ESO also partnered with the United Kingdom in an Advanced Electric Power and Propulsion Project to develop a power system architecture for future ships. A focus of this project agreement is enabling technologies for dc distributions systems.

In April 2013, the U.S. Navy issued an update to the NGIPS Technology Development Roadmap [now called Naval Power System (NPS) Technology Development Roadmap (TDR)] to reflect significant changes in the acquisition environment [15]:

- the DDG 1000 program was truncated to three ships;
- the CG(X) cruiser was eliminated from the 30 year shipbuilding plan;
- the DDG(X) shifted from FY 23 to FY 31;
- fuel savings became a high priority for both in-service ships and new construction ships.

While the previous TDR was organized around different power system architectures, this TDR focused on six product areas:

- controls;
- distribution;
- energy storage;
- electrical rotating machines;
- power converters;
- prime movers.

This TDR made specific recommendations for technology developments. The NPS TDR recommends that in the near term (2013–2022) the Navy should focus on developing:

- An *Energy Magazine* (along with an associated advanced mission system power upgrade) to provide a multiuse energy storage to support pulse power loads, improve system stability, provide backup power, and be able to integrate with existing distribution voltages on multiple platforms;
- an energy recovery system compatible with both gas turbine and diesel prime movers to improve energy efficiency;
- military qualified medium-voltage (4160 V) vacuum circuit breaker switchboards that will fit within the existing air circuit breaker switchboard envelopes;
- a reduced scale advanced development (RSAD) medium-voltage dc (MVDC) power distribution system to support future destroyer and littoral combat ship designs;
- advanced MVDC circuit protection;
- a universal ship's power management controller.

The NPS TDR also recommends research into advanced conductors and advanced solid state energy recovery. An update to the 2013 NPS TDR is currently underway.

In parallel with the ESO efforts, SEA 05, as detailed by Doerry and Moniri [6], is updating the technical standards, specifications, design data sheets, and design criteria and practices manuals comprising the electric warship technical architecture. This technical architecture is key to the repeatable and affordable development of power systems meeting the needs of our naval forces.

B. High-Power Radars

In the late 20th century, the Navy was not concerned about the ballistic missile threat to its fleet. Rather, ballistic missile defense concentrated on the threat to forces within a theater (generally understood to be land forces) and to the continental United States [12]. An initial capability was established through upgrades to the AEGIS weapon system and employing the SPY-1 phased-array radar.

Radar development during the first decade of the 21st century focused on improving performance against aircraft and the cruise missile defense. The dual band radar (DBR) consists of an X-band SPY-3 multifunction radar (MFR) for horizon search, low-altitude tracking, and missile support and an S-Band volume search radar (VSR) for searching and tracking higher altitude targets. A common controller integrated these two radars with the combat system. The DBR is common to the DDG 1000 and CVN 78 designs. However, in 2010, in order to reduce cost, the Navy eliminated the VSR from the DDG 1000 design and reallocated VSR requirements to the MFR for the three ships of this class.

During the first decade of the 21st century, anti-ship ballistic missiles (ASBMs) became a new threat to our fleet. The high terminal speed of these weapons was anticipated to exceed the capabilities of terminal defense systems. New defensive systems would be required. With current technology, radars able to detect and track the ASBM threat would be significantly larger than the SPY-1 radars and require significantly more electrical power.

While the DBR technically advanced shipboard radar capability, the DDG 1000 selected acquisition report (SAR) dated December 31, 2011, stated [25]:

> The FY 2011 President's Budget (PB) submission confirmed the reduction of the DDG 1000 Program to three ships as a result of the Future Surface Combatant Radar Hull Study in which the Navy concluded that a modified DDG 51 with an Advanced Missile Defense Radar (AMDR) is the most cost-effective solution for fleet air and missile defense requirements.

The Navy is developing the AMDR to provide an inherent capability for ballistic missile defense in addition to traditional air threats. The AMDR will be scalable so that the largest achievable size that can be integrated in the DDG 51 Flight III will be initially produced, while still enabling larger arrays for future classes of ships (such as a potential Flight IV in the 2032 time frame) to meet evolving threat capabilities [9].

To meet the increased power required by the Flight III for the AMDR and other combat systems modifications, the traditional 450-V distribution system with three 3-MW generators will be replaced with a 4160-V distribution system featuring three 4-MW generators [23]. As the ASBM threat evolves over the next decades, radar power levels will likely continue to increase, resulting in even more electrical power demand from the ship's power system. IPSs will likely be the most affordable means to provide this power in a new design ship.

C. Electric Weapons

Electric weapons are on the verge of becoming reality [21]. In 2014, the U.S. Navy will deploy a solid state laser weapon on *USS Ponce*. The LaWS has been demonstrated in tests against remotely piloted aircraft and surface craft [19]. The introduction of lasers and railguns into the fleet will realize the 1989 vision for Cluster E. While initial deployments of these weapons, such as the installation of a laser on *USS Ponce*, will likely be into non-IPS ships, the full potential of these weapons will not be realized until the Navy transitions to IPS-based ships; power from prime movers normally used for propulsion will be shared with the weapons systems.

Railguns use extremely high pulses of currents (millions of amperes) to create electromagnetic forces for propelling projectiles at speeds much greater than achievable with traditional chemical propellants. Railguns offer the potential to reach targets in the hundreds of nautical miles away and destroy targets with the projectile's kinetic energy. The amount of explosive propellants and projectiles can, therefore, be significantly reduced onboard future electric warships. Railguns can support a variety of missions including naval gunfire support, cruise and ballistic missile defense, anti-air warfare, and defense against waterborne threats [18].

To date, a tactically useful railgun has not been developed. In World War I and World War II, experimental railguns were produced and tested. By 1945, projectile velocities of 1200 m/s were achieved, but the research did not result in fielded systems. In the 1970s and 1980s, several countries, including the United States, conducted research in railgun technology. These efforts resulted in experimental railguns capable of achieving 8 MJ and greater muzzle energies [14].

The current effort to develop a tactical railgun in the United States began in August 2005 with the initiation of the ONR railgun innovative naval prototype (INP). Between 2005 and 2011, phase I of this program was able to advance railgun technology in many ways. Muzzle energy increased from 6 MJ to a world record in excess of 32 MJ. Bore life was improved from tens of shots to hundreds of shots, pulsed power systems experienced a 2.5 times increase in energy density, and actual projectile flight bodies have been propelled on an open range [7].

Phase II of the railgun INP started in 2012. During this phase, technology is being matured for transition to an acquisition program. Technology developments include demonstrating a 10-rounds/min firing rate including thermal management for both the launcher and the pulsed power system. A prototype launcher is scheduled to be delivered to the Navy in 2014 for testing. In 2016, the Navy plans to install and test a prototype railgun on a joint high-speed vessel (JHSV) [16].

D. Technology Trends

In [13], McBride provides a well-researched description of general technology adoption by the U.S. Navy up to the beginning of the Cold War. Chapter 4 of this book, "Technological Trajectory: Geostrategic Design Criteria, Turboelectric Propulsion, and Naval-Industrial Relations," besides providing a high-level discussion of early implementation of electric propulsion in U.S. Navy ships, emphasizes the fact that technologies are adopted that support the U.S. Navy's implementation of the high-level national strategy. This national strategy is at least, in part, a response to perceived threats and the technological capabilities of potential threats. These perceived or potential threats are uncertain and change as time passes. Contemporary thinking within the U.S. Navy acknowledges that this uncertainty in and technological change through time itself poses a threat worthy of the development of a countermeasure. Future trends will be analogous to historical, general naval technology adoption trends and, specifically, electric power technology adoption trends.

1) Trend One—Less Time to Integrate Emerging Technologies: In the past, before the transistor, the service life of naval ships was on the order of technology development time scales. Ships' service lives were not as long then as today. Naval technology took longer to develop and deploy then. Largely, the ship itself was the desired technology artifact, a complete, integrated sensor weapons platform whole. Over the past 70 years or so, this has changed. Ships' service lives are now much longer than technology development time scales. This is forcing the Navy to rethink how it designs its ships in terms of integrating weapons, sensors, and the platform.

Trend One can lead down two different paths: 1) the Navy can acquire highly integrated sensor weapons platforms, operate them briefly, then acquire a newer technology highly integrated sensor-weapons-platform version; and 2) the Navy can acquire a longer lived platform into which the more ephemeral mission systems can be relatively quickly and easily integrated and then update the mission systems as soon as newer technology versions are available. Doubtless, the path taken will be heavily influenced by affordability concerns.

2) Trend Two—Increasing Complexity of the Integration of Technologies: Historically, naval combatants' machinery systems have usually featured high-quality, state-of-the-art, high-performance equipment. The nature of this equipment has been driven by some military-unique requirements and the need for a compact machinery system. The penchant for compactness leads to a high degree of hull/equipment integration. The machinery spaces are "tight" with little additional room to spare for additions or modifications. Classical naval power system design assumes an electromechanical technology base, with rotating machines supplying analog (electromechanical) loads, at least the large loads anyway. Naval power system design guidelines and practices have not yet changed to take advantage of the information technology base and the power electronic technology base vice the electromechanical technology base.

With the inception of information technology and ubiquitous computer control of sensors and weapons to achieve superior (faster than human) performance, integration of new technology systems, including sensors, weapons and power systems, requires more than simply providing an electric feeder cable and cooling water; integration into the overall ship control system is necessary.

Trend Two leads the Navy back to the same two paths posed by Trend One; however, it adds detail to each path. The first path, highly integrated sensor weapons platforms, must have acknowledged the increased degree of integration complexity. The second path, longer lived platforms with ephemeral mission systems, will require a nonrecurring engineering investment for the Navy to successfully specify ship-mission-open interfaces; the Navy must learn generalized integration through standardized interfaces.

3) Trend Three—More Focused Investments in Technology Development: Leading into World War II and certainly throughout the Cold War, technology development in the United States was dominated by defense-funded research and development. The military, in general, and the Navy, specifically, represented a significant market which drew broad industrial participation, in all the phases of research and development, from basic research to engineering/production development. Since the end of the Cold War, defense-funded research and development has decreased as a percentage of all research and development funding in the United States. The military and the Navy no longer comprise a major market. Not being able to fund the breadth and depth of research and development as in the past, future research and development funding is likely to be focused more narrowly in Navy-unique domains, while commercially derived products are leveraged for the Navy's more generalized requirements.

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