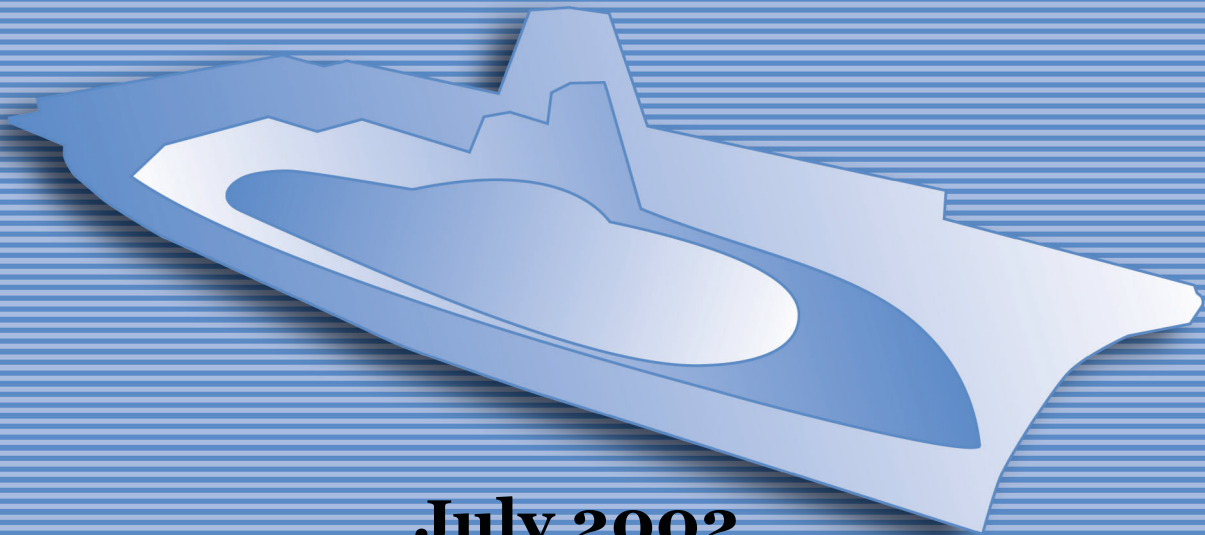




Naval Research Advisory  
Committee Report



# Roadmap to an Electric Naval Force



**July 2002**

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OFFICE OF THE ASSISTANT SECRETARY OF THE NAVY  
(RESEARCH, DEVELOPMENT AND ACQUISITION)

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**14. ABSTRACT**

NRAC was tasked to assess the increasing electrification of the traditionally mechanical US Navy. Specifically, the Panel was asked to study recent trends and developments; recommend a power system architecture; and, recommend a science and technology roadmap for development of an integrated electric naval force.

The Panel reviewed commercial electrical marine applications worldwide and the various naval electric propulsion, auxiliary, sensor, and weapons programs in the US and UK from both a historical and current prospective. They found that there is an evolving industrial base for electric ships and that the DD(X), LHD8, CVNX and the VIRGINIA SSN provide a naval electric ship baseline.

To realize the full potential of electrification, the Panel determined the Navy needed to develop an Electric Warship with a common electric power system that would allow all the power in a ship to be available for propulsion, sensors or weapons as needed. The development of the Electric Warship will then allow evolution to the Electric Naval Force where power is available to off-board units.

In order to achieve the warfighting superiority of the Electric Naval Force, the DoN should establish central responsibility to develop and manage balanced (weapons, sensors, and propulsion) technology investment strategy.

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**July 2002**

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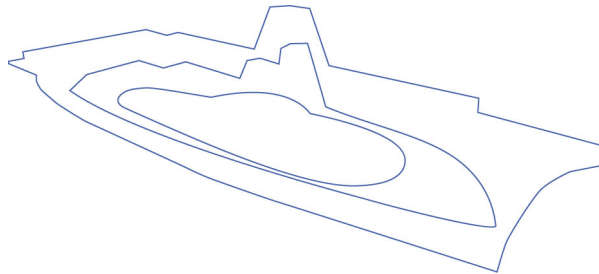
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# ROADMAP TO AN ELECTRIC NAVAL FORCE



**“The Navy is committed to fielding electric powered warships.”**

**CNO Executive Board**

**2 March 2001**

## **Introduction**

In February 2001 Mr. Paul Schneider, Acting Assistant Secretary of the Navy (Research, Development and Acquisition) [ASN(RD&A)] charged the Naval Research Advisory Committee (NRAC) to perform a study entitled “Roadmap to an Electric Naval Force.” The context of the study is the increasing electrification of traditionally mechanical marine and naval functions. The naval electrification process offers improved affordability through reduced maintenance, more efficient operation, enhanced commonality and compatibility with automatic sensing and control. It also portends a shift of the industrial base away from traditional mechanical disciplines upon which the Navy has relied throughout the 20<sup>th</sup> century.

Several events that occurred during the course of the study serve to underline its timeliness. In March, the Chief of Naval Operations (CNO) Executive Board issued the statement quoted on the cover of the report and shortly thereafter the CNO appointed a flag level Electric Warship Strategy Task Force to recommend the course that the Navy should pursue. During the summer, the Office of Naval Research (ONR) identified “Electric Warship” as a proposed Future Naval Capability. The overall effect of these parallel events upon this NRAC study was to shift the panel deliberations away from why the Navy should pursue an Electric Naval Force, toward how the newly emerging electric-based technologies might be most beneficially implemented.

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## Executive Summary



- Evolving industrial base in electric ships
- DD(x), et al, - naval electric ship baseline
- Electric Warships unlock propulsion power for electric weapons and advanced sensors
- Flexibility of naval electric power architecture supports evolution to Electric Naval Force
- Central responsibility for Electric Warship technologies essential to achieve warfighting superiority

### Executive Summary

A rapidly evolving industrial base in marine electric technology provides a sound basis for evolution to all electric ships in which propulsion and auxiliaries are powered by common electric power sources. However this industrial base, focused upon principally commercial ships, has not addressed Navy specific concerns such as shock hardening and signatures. The new generation of Navy ships, LHD8, DD(X), CVNX, and VIRGINIA SSN, will address these issues and provide the naval electric ship baseline upon which this study is based.

Electric weapons and advanced, high-power, sensors offer the superior warfighting capabilities such as deeper magazines, longer range, higher rates of fire, precision strike, quicker time to target, and longer-range higher-resolution sensors necessary for the 21<sup>st</sup> century environment. However, the large amount of electric power these systems will require makes current shipboard electric systems impractical. Making all shipboard power available electrically enables the integration of such advanced weapons and sensors to create Electric Warships. The flexibility of the resulting naval electric power architecture allows Electric Warships to provide power to offboard weapons and sensors as well as forces ashore. This is the recommended route to create a technically superior Electric Naval Force.

In order for the Department of the Navy (DON) to realize the benefits of superior warfighting capabilities, affordability, reduced workload, commonality and reduced logistics burden, it is necessary to centralize the responsibility for developing the enabling technologies for the Navy's future Electric Warships.

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## Terms of Reference

### For an Electric Naval Force



- **Review and assess recent trends and developments** in the application of electric power to naval platforms as well as weapons and auxiliary systems.
- **Recommend a power system architecture** for optimum long-term exploitation of the benefits of integrated power systems for naval forces.
- **Recommend a science and technology roadmap** for the development of an integrated electric naval force and identify possible roadblocks to its successful realization.

### Terms of Reference

Naval forces are on the verge of a revolution in the distribution, control and utilization of power onboard weapons platforms. All-electric ships, boats and combat vehicles offer the promise of improved performance, increased versatility, and lower cost of ownership. In order to take full advantage of the opportunities offered by integrated electric power systems, a power system architecture that will facilitate flexibility in operation, rapid recovery from damage, ease of maintenance, and ready integration of new technologies, as they become available, is essential.

The Terms of Reference (TOR) for the NRAC “Roadmap to an Electric Naval Force” study charged the panel to assess the state of the art of naval relevant electric technologies, recommend an architecture for optimum exploitation and lay out a roadmap for development. The full text of the TOR is presented in Appendix A.

The panel decided early in the study that the advantages of electric propulsion and electrification of auxiliaries were well understood by naval architects and engineers and chose to focus instead on the question of why, after more than a decade of successful commercial applications, the Navy has not yet fielded a single modern electric ship. The panel’s conclusion was that the compelling advantage to the warfighter had not yet been convincingly articulated. This is where the panel efforts were focused.

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## Panel Membership



<u>Chairperson</u>			
Prof. William F. Weldon*	Professor Emeritus, Univ. of Texas at Austin	Dr. William A. Neal, M.D.* CDR Paul T. Norton, RN (Ret.) LtGen Keith A. Smith, USMCR (Ret.)	West Virginia University Alstom Power Conversion Ltd
<u>Vice Chairperson</u>			
Mr. Peter A. Gale*	J J. McMullen Associates, Inc.	Dr. Jason Stamp	Private Consultant
Mr. R. Michael Adair	GD Bath Iron Works	Mr. Howard Stevens	Sandia National Laboratories
Mr. Mark Adamiak	GE Power Management	RADM John T. Tozzi,	Anteon Corporation
Mr. Clifford L. Allen, P.E.	Ingalls Shipbuilding, Inc.	USCG (Ret.)	SYNTEK Technologies Corporation
Dr. Robert W. Ashton	Naval Postgraduate School	Mr. Timothy J. Winter	Northrop Grumman Corporation
Mr. Charles H. Brown, Jr.	SYNTEK Technologies Corporation	CDR Stuart Young, RN	Defence Procurement Agency, MoD
RADM Lewis A. Felton, USN (Ret.)	Private Consultant	<u>Study Coordinator</u>	
Dr. Robert Fischl	F&H Applied Science Associates, Inc.	RADM George R. Yount, USN	Naval Sea Systems Command
Mr. John H. Gully	Science Applications International Corporation	Mr. David Clayton	Naval Sea System Command
Dr. Eric Horvitz*	Microsoft Research	<u>Executive Secretary</u>	
Dr. James E. Hubbard, Jr*	IproVica	CAPT Dennis L. Ryan, III	ONR
VADM E.R. "Rudy" Kohn, Jr USN (Ret.)	Private Consultant	USN (Ret.)	
Mr. Maxwell Mulholland	America Superconductor	CAPT Leo G. Dominique, USN (Ret.)	Noesis, Inc.
		CDR Joe S. Konicki, USN	Naval Sea System Command
*NRAC Member			

### Panel Membership

The NRAC “Roadmap to an Electric Naval Force” panel was chaired by Professor William Weldon, and Mr. Pete Gale served as vice chairperson. The study panel consisted of members of NRAC (marked by \* on the chart above), Navy, Marine Corps and Coast Guard retired flag and general officers, and outside experts representing the naval and commercial marine industrial base, the commercial electrical technology community and the United Kingdom’s Royal Navy electric ship experience. The panel was unusually large for an NRAC panel, reflecting the wide range of expertise necessary to address the study topic. Details of panel member affiliations are included in Appendix B.

The Study Coordinator was Rear Admiral George Yount, USN, Deputy Commander Integrated Warfare Systems, Naval Sea Systems Command (NAVSEA). RADM Yount appointed Mr. David Clayton as technical point of contact for the panel. Mr. Clayton did an exemplary job of providing technical information and arranging briefings as well as attending all panel meetings and the summer study.

The Executive Secretary for the study was Captain Dennis Ryan, USN (Ret.) who did an outstanding job of supporting the panel effort and was ably assisted by Captain Leo Dominique, USN(Ret.) and Commander Joe Konicki, USN.

As always the panel’s job was made easier and more pleasant by the capable support of the NRAC staff.

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## Input to Panel



- **40 Technical Briefs**
  - CINCLANTFLT
  - NAVSEA
  - NAVAIR
  - N70
  - ONR
  - SSG
  - USCG
  - UK Royal Navy
  - Newport News Shipbuilding
  - Alstom
  - Sandia National Lab
- **3 Field Trips**
  - IPS
  - GTS Infinity
  - Brooks AFB
- **33 Papers & Reports**
  - USMC Electric Power Requirements
  - Quadrennial Defense Review Report - 2001

### Input to Panel

Prior to the two week summer study, the panel received 34 briefings, made three field trips and reviewed numerous documents in order to ensure an up-to-date understanding of past Navy experience with electric technology, the current state of Navy commitment to electric ships, future Navy thinking regarding the evolution and application of electric technology, and the current state and direction of applicable marine and commercial electric technology. A complete listing of all briefings and reference material is included in Appendix C.

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## Outline



- Need - Naval Superiority
- Opportunities - Electric Technologies
- Pathway -
  - Electric Ships → Electric Warships → Electric Naval Force
- Crosscutting Concerns
- Conclusions & Recommendations

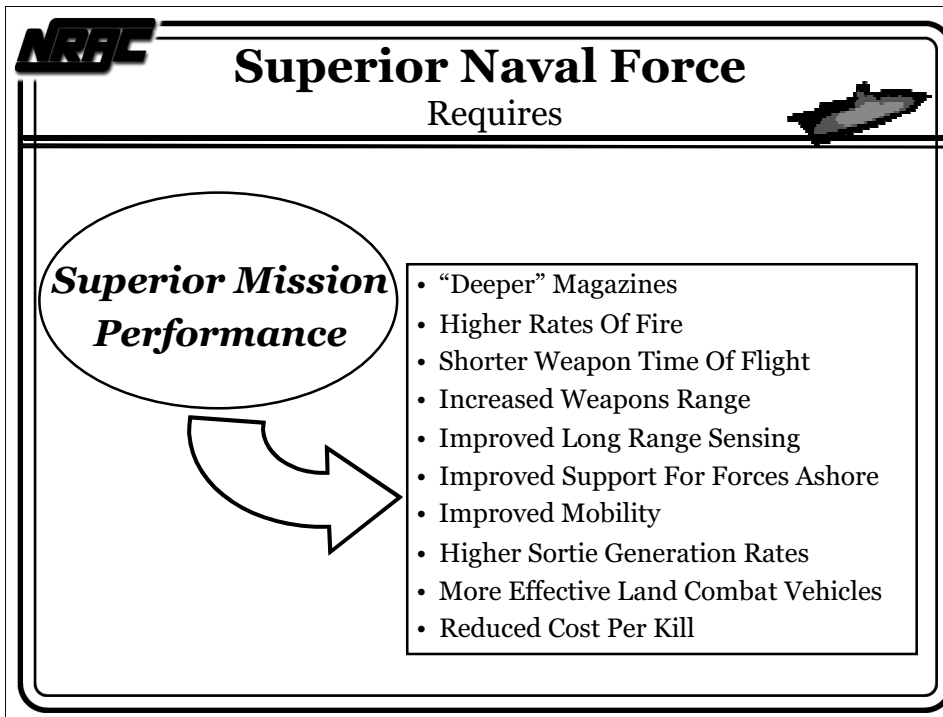
### Outline

This report first discusses the warfighting capabilities necessary to ensure a superior naval force and then explores the corresponding opportunities afforded by existing and emerging electric technologies.

The report then lays out a recommended pathway for evolution from the electric ships under development today (integrated electric power for electric propulsion and auxiliaries), through Electric Warships (common electric power for propulsion, auxiliaries, weapons and sensors) to a technically superior Electric Naval Force wherein Electric Warships provide power to offboard sensors, weapons and forces ashore. Panel assessments of appropriate areas for technology investment are presented for four Electric Naval Force technology areas: (1) electric propulsion and auxiliaries; (2) common electric power system; (3) electric weapons and advanced sensors; and (4) support for offboard weapons, sensors and forces ashore.

Finally, issues that cut across all Electric Naval Force technology areas are discussed before presenting the panel's recommendations and conclusions.

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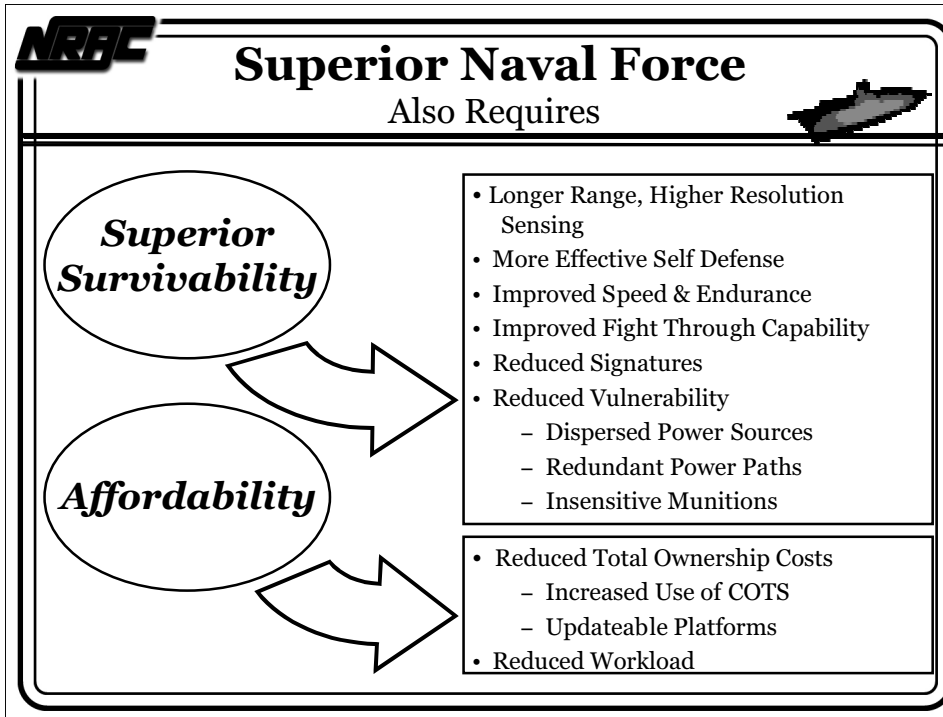
### Superior Naval Force

The United States has maintained a technically superior naval force throughout the last century by early recognition and implementation of leading-edge technologies. A technically superior naval force is essential to our national security and has endured as a key element of our national military strategy.

A relatively small 21<sup>st</sup> century naval force will be required to respond to rapidly evolving conflicts throughout the world. Diffuse adversaries, spread among non-combatant populations will present numerous low value targets. Nonetheless these adversaries will often be well equipped with advanced weapons, including theater ballistic missiles—thus representing a formidable threat to force security. The close proximity of non-combatants, increasing need for coalition support of military action, and pervasive presence of television news images all combine to render collateral damage increasingly unacceptable. The requirement to support (often diffuse) forces ashore in these environments will continue to become more challenging.

Successfully defeating numerous, diffuse, low value targets requires improved firepower, surgically precise targeting and weapon delivery, higher rates of fire, longer ranges, more rounds in the magazine and lower cost-per-kill weapons. The mobility of such targets demands shorter weapon time of flight and improved long range sensing. The capabilities described in this and the following chart directly support the strategic and tactical tenets for the naval force of the future as defined in: **...From the Sea, Forward...From the Sea, Operational Maneuver From the Sea**, and **Joint Vision 2010**.

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**Superior Naval Force (cont.)**

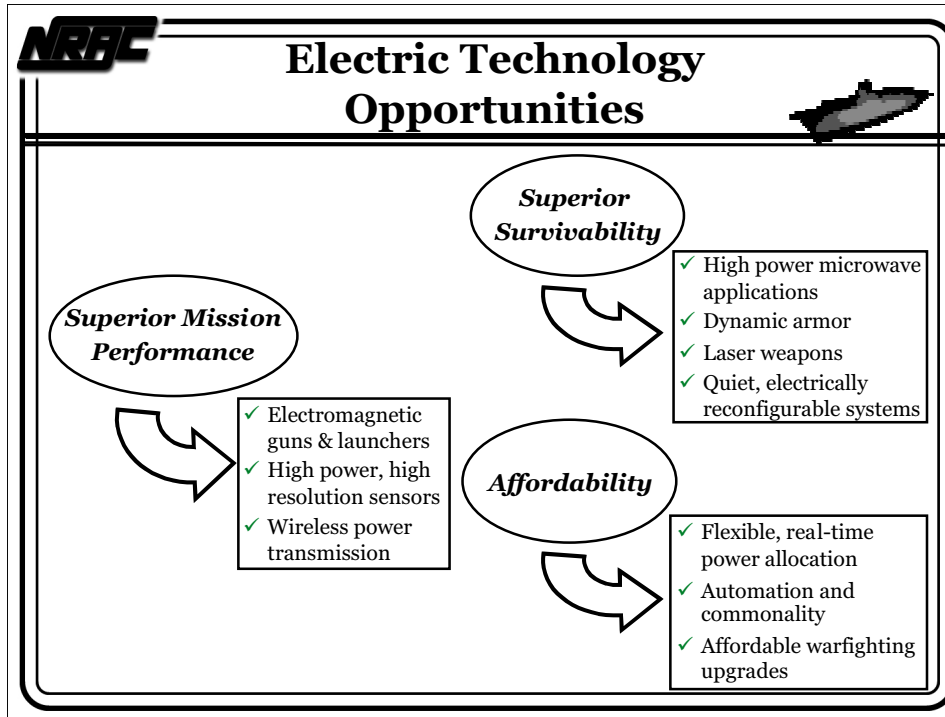
To be effective, the naval force of the future must also be capable of surviving in the same high-threat environment described above. This requires the ability to avoid detection, detect threats early, defend against those threats and continue to function effectively in the event of damage. The anticipated size of the future naval force coupled with the rapidity of crisis evolution and diffusivity of the threat make mobility and endurance more critical than ever to the survivability of an effective force.

Finally, the reality of 21<sup>st</sup> century budgets demands that all these capabilities be affordable. With appropriate up front investments, Electric Warships can cost considerably less to operate and maintain than present-day assets—freeing operational resources so that they may be applied to further advancements in combat capabilities.

The future naval force must successfully execute all naval missions; however, power projection and theater ballistic missile defense are, by far, the most demanding. The total capability required to provide overall mission performance, which includes lethality, mobility, sustainability and survivability, cannot be affordably provided using current technologies. More capable and cost efficient weapons, sensors, launchers, and land vehicles are required, as well as improved platform speed, endurance, and self-defense.

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## **Electric Technology Opportunities**

The ability to project power and conduct theater ballistic missile defense are definitive requirements for the future Naval force. Emerging electric technologies, as shown above, offer the promise of enhanced capabilities to meet these requirements.

A common power system architecture that allows transfer of electric power from ship's service and propulsion systems to advanced electric weapons, sensors and countermeasures can provide a realistic, affordable, leap-ahead capability.

Electromagnetic aircraft launchers and arresting gear (EMALS and EARS) offer increased mission effectiveness by reducing peak loads on the airframes and reducing manpower needed to man the catapult and recovery systems. EMALS also has a significant impact on ship architecture and the nuclear power plant by reducing the demand for large quantities of steam. Future electromagnetic (EM) launchers can also provide the capability for quiet, controlled launch of torpedoes, countermeasures and unmanned systems.

Volume of fire and fire support for marines ashore are critical. EM guns provide "deep magazines" by using the weapon platform fuel supply and improve shipboard survivability by eliminating propellants. Because the rounds do not require propellant they are significantly smaller than conventional rounds. Therefore, the number of rounds in a given magazine can be increased by 40 to 100%. The velocity of EM launched projectiles is 2-3 times faster than conventional rounds, which correspondingly reduces time of flight and increases range (200-300 miles). Because EM gun projectile trajectories are ballistic, the guidance and control systems are simpler, more reliable and more affordable than those required for rocket assisted rounds like the Extended Range Gun Mmunition (ERGM). Although the Army has the lead in developing EM guns, Naval fire support requirements are

less stringent than Army requirements for direct fire weapons, i.e. lower power supply density and reduced gun pressures.

High-power radars also provide a leap-ahead capability—once again enabled by availability of electric power redirected from the ship power/propulsion. Radars in the 4-6 megawatt (MW) range can provide over-the-horizon sensing, tracking and discrimination of incoming cruise missiles. Radars in the 16-20 MW range can provide the capability to sense, track and discriminate low radar cross section theater ballistic missiles in high clutter (chaff) environments.

Ashore, Hybrid Electric Combat Vehicles (HECVs) offer increased lethality, mobility and survivability. Electric propulsion with active electromagnetic suspension provides unparalleled mobility for wheeled vehicles in soft soil while also providing rapid acceleration and hill climbing capabilities. The common electric power system can also provide pulsed power for electric weapons including electro-thermal guns, microwaves, and lasers. Although initially powered by diesel engines or small gas turbines, HECVs can be converted to fuel cells as they become available. Fuel cells offer improved fuel efficiency, reduced thermal and acoustic signatures and generate water—a key logistics enabler. With the development of onboard diesel reformers, the Electric Warship could generate and supply hydrogen for HECVs, and offboard weapon and sensor fuel cells. Ultimately the capability to transmit electric power from the Electric Warship directly to offboard assets may be developed.

Alternate power sources for personnel are a critical issue. Rechargeable batteries, fuel cells, and micro-engines are all potential near and intermediate term technologies to address the logistics problems of carrying and disposing of heavy primary batteries. The HECV would recharge batteries for Marine equipment, including sensors, weapons, communications, night vision, computers, and personnel protection systems. HECVs could also be used to replace trailer-mounted generator sets for tactical operation centers and battlefield power. Battlefield sensors, such as unattended ground and seabed sensors, will become ever more effective with improvements in small power supplies.

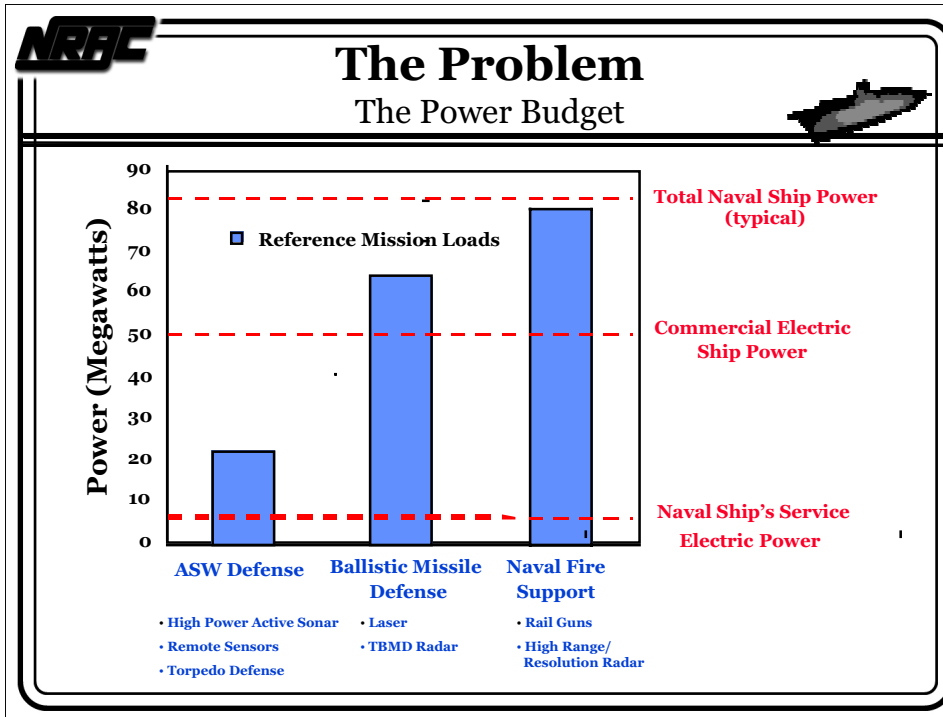
The inherently low signatures characteristic of electric power systems and the ability to rapidly reconfigure the systems for damage control are unique and fundamental to survivability. Electric power systems also support advanced countermeasures such as: high-power microwaves for anti-personnel, non-lethal applications (active denial) and electronic countermeasures; dynamic armor for protecting critical or vulnerable systems such as magazines against shaped charge warheads; and advanced lasers for future air defense.

Electric power systems, to replace mechanical, hydraulic or pneumatic systems, are being developed for both commercial and military applications because they offer higher performance at reduced cost. Automation, commonality of components and built-in diagnostics are more readily implemented with electric power systems and provide fundamental advantages. The cost per round and cost per kill for both the EM gun and future directed energy weapons will be much lower than for today's weapons. This benefit is amplified by the deep magazines and reduced logistics associated with these weapons.

Affordability of the naval force, long-term, will be enhanced by the “plug and play” approach to upgrading power systems, weapons, sensors and countermeasures inherent in the advanced, open architecture envisioned by the Panel. For instance, when a more efficient motor controller or a more compact energy storage device or a more effective weapon, sensor or countermeasure is developed, they are easily integrated into the system. An open, flexible power system architecture is essential to realize these benefits.

These requirements can only be fulfilled by a common, flexible, robust architecture that permits the dynamic allocation of large amounts of power to mission systems (including weapons, propulsion, and self-defense), as needed. Current warship designs, in which up to 90% of installed power is dedicated solely to propulsion, cannot provide the needed capability. Electric Warships can fulfill the requirements for the technically superior future naval force.

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## The Problem

Electric based technologies offer the most attractive and affordable route to achieving the superior naval force of the future, but total ship power must be available for all demands of the mission. Typical reference mission scenarios for future Electric Warships<sup>1</sup> require high power (many tens of megawatts) for the required combinations of advanced electric powered weapons and sensors, propulsion, and ship's service functions. The total electric load for these future warfighting scenarios far exceeds the ship's service electrical power capacity of surface combatants. Although the typical Navy surface combatant of today has a total installed power of over 80 MW, up to 90% of that power is locked up in the propulsion system and not available for the weapons and sensors needed to achieve warfighting superiority.

It is important to note that the very high weapons and sensors power required from the ship's power system is only required for relatively brief operating periods, so that the effect on ship mission mobility is minimal. By designing a power system architecture to meet both mobility and enhanced warfighting challenges, the DON will also reap the already well-articulated performance and affordability benefits of electric drive and integrated power systems while providing the power necessary to achieve a superior naval force.

<sup>1</sup> *All Electric Ship Concept Assessment Studies, Mr. Jeff Peters, NSWC Carderock*

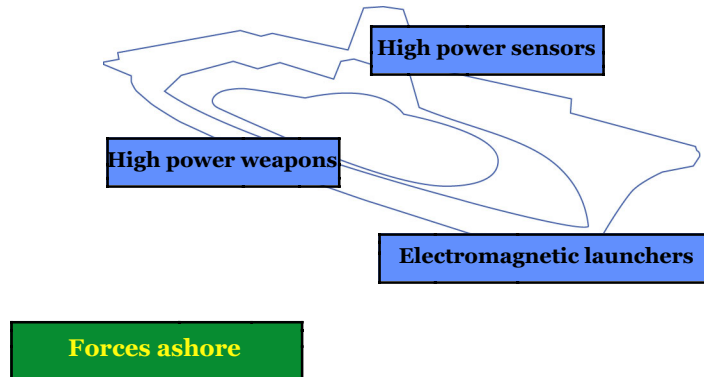
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## The Solution



### Unlock Propulsion Power to Enable Superior Warfighting Capability

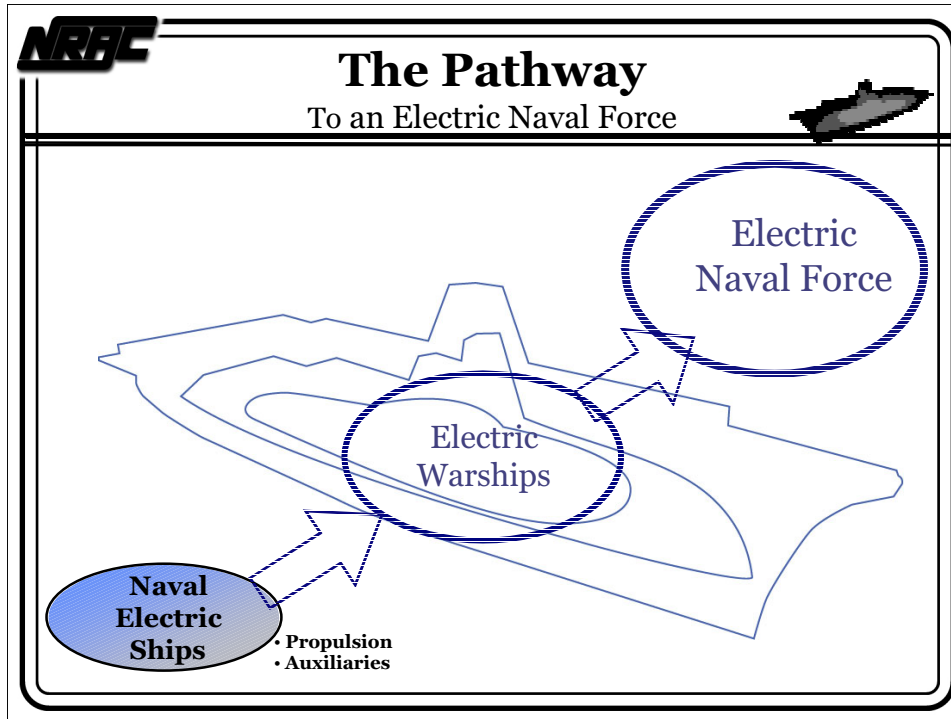


### The Solution

Today, up to 90% of a warship's power may be dedicated to propulsion. The power requirements of future platforms and combat systems will increase ship's service and auxiliary power levels well above the practical limit of current warship power architectures. The only reasonable means to overcome this dilemma is to unlock propulsion power and implement a common, flexible, robust architecture that permits the dynamic allocation of large amounts of power to mission systems (including weapons, propulsion, and self-defense), as needed. "Unlocking" this propulsion power for weapons and sensors by converting it to electricity will provide the required warfighting capabilities without the need for separate dedicated power supplies which can make such capabilities unattractive. Conversely, extra power for high-power weapons can also be used for enhanced propulsion capability.

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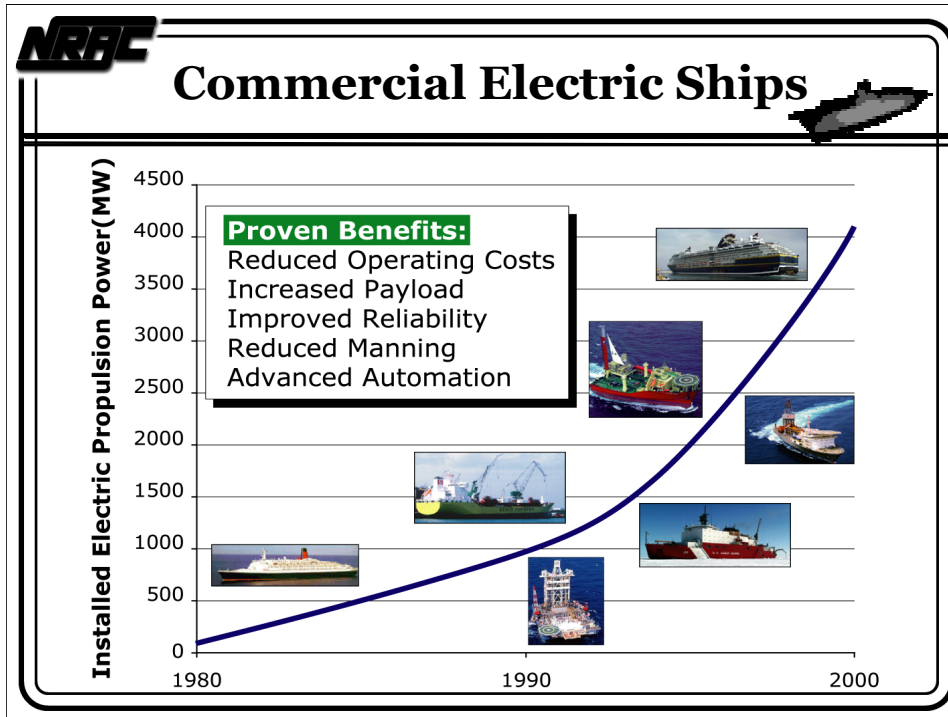


### **The Pathway**

The keys to the superior naval force of the future, based on emerging electric technologies described herein, are Electric Warships. Electric Warships integrate all ship and mission systems through a common electric power system, thus making the full resources of all power generation, energy storage, and pulse power capability available to best support mission priorities. The role of the common electric power system will expand from supplying shipboard power to onboard weapons and sensors as well as propulsion and ship's services, ultimately providing power to offboard sensors and weapons, including forces ashore. This will lead to the realization of the technically superior Electric Naval Force.

Emerging Navy electric ships such as the LHD8, DD(X), CVNX, and Virginia SSN are precursors for the Electric Warships of the future. Although the electric weapons and advanced sensors envisioned for Electric Warships are not available today and therefore the requirement to make all shipboard power available on the electric distribution system does not yet exist, these new Navy electric ships should be built with the maximum degree of electrification practicable, including consideration for future electric technology insertion. Otherwise, new advanced systems may not be fielded because of insufficient electric power in our future naval warships.

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## Commercial Electric Ships

The last two decades have seen impressive growth in the application of marine electric propulsion to commercial ships including cruise ships, ice breakers, and shuttle tankers. These advances are now making their way into the design of high-speed cargo ships and even into the design of the U.S. Navy's new combat logistics ship, T-AKE1. This transition has been made largely due to the availability of high power, variable frequency, converter drives enabled by advances in power electronics technologies and by the resulting evolution of external, podded electric propulsors. The growth is largely due to the positive impact upon ship construction and operation as outlined in the chart above. In (c.1998) conversion from mechanical drive to podded electrical drive, Carnival Cruise Lines realized a fuel savings of 40 tons/week (8%) for each ship<sup>2</sup>.

Along with the benefits of electric marine propulsion comes the inevitable shift of the industrial base from traditional mechanical technologies to newly emerging electric technologies. Although the commercial marine electric products are not directly applicable to Navy ships, since they are not designed with shock or reduced signature requirements in mind, they nevertheless have gone a long way toward establishing a new electrical technology industrial base. As a result, the mechanical technology industrial base, upon which the Navy has long relied, is eroding.

<sup>2</sup>Elation-Fantasy Class Cruise Liner, Finland <<http://www.ship-technology.com/projects/elation/>>

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## Naval Electric Ships

Provide Today's Baseline



- LHD8
  - Electric auxiliaries
  - Partially integrated electric power
- DD(X)
  - Naval electric propulsion
  - Integrated power system
- CVNX
  - Large naval turbine generator
  - High voltage, high power distribution system
  - EMALS
  - Electric auxiliaries
- VIRGINIA SSN
  - Power conversion technology

### Naval Electric Ships

The present generation of Navy ship acquisition programs set the technology baseline for the panel's assessment and recommendations. These electric ships will clearly contribute to the technology necessary to realize the next generation of Electric Warships.

LHD8 utilizes two LM2500+ gas turbines for propulsion, each driving a controllable pitch propeller at 35000 horsepower (HP) per shaft. In addition, it employs two 5000 HP auxiliary electric propulsion motors powered from the ship's electrical system and driven by variable speed drives connected to the two reduction gears. Power to the auxiliary propulsion motors can be cross-connected from the port or starboard busses or from isolated generators. This results in a partially Integrated Power System.

Conversion of all steam heat to electric heating led to a significant increase in electric load. Consequently, the power generation system utilizes six diesel generators, each rated at 4 MW at 4160 volts, which are dispersed forward to aft throughout the ship. The ship's power distribution architecture utilizes a port and starboard zonal system wherein the 4160-volt longitudinal busses are configured high and low with a minimum of two deck vertical separation. Within each zone, the power is distributed radially. Since each fire zone boundary is also a corresponding electrical zone boundary and power is not distributed across the zone boundaries, each fire zone can be electrically isolated, and power can be readily reconfigured and still be available to the other electric zones from the dispersed generators.

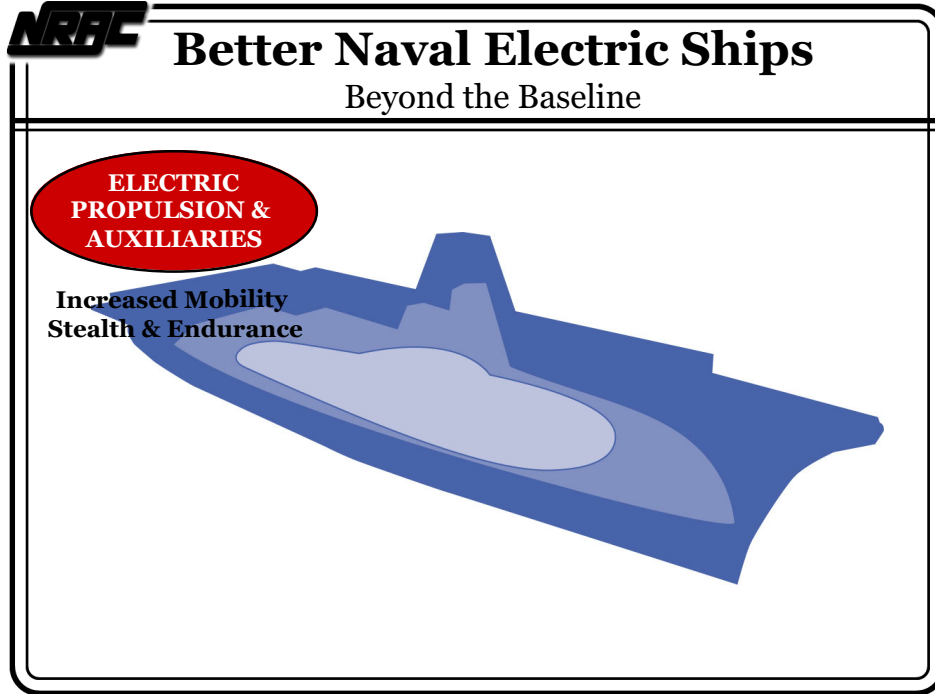
Delays in the DD21 downselect resulted in details of the technology being developed for DD21 not being available to the panel. Regardless, the challenging requirements and public statements by the Navy give good indication that DD21

would have moved the technology baseline forward significantly. In January 2000, then-Secretary of the Navy Danzig announced that DD21 would be the first class of Navy warships designed and built in the 21<sup>st</sup> century to be powered by electric drive featuring an integrated power architecture. Underscoring the importance of using integrated power technologies, the Secretary said:

“Changes in propulsion systems fundamentally change the character and power of our forces. This has been shown by the movement from sail to steam or from propeller to jet engines or to nuclear power. Electric drive will reduce the cost, noise and maintenance demands of how our ships are driven. More importantly, electric drive, like other propulsion changes, will open immense opportunities for redesigning ship architecture, reducing manpower, improving ship life, reducing vulnerability and allocating a great deal more power to warfighting applications.”

This visionary statement has been pursued by not only funding the DD(X)—DD21 has been restructured into the DD(X)—power system design but by directing some of the funding to innovative new technologies which have been assessed by the Navy as supporting both the DD(X) requirements and other Electric Ship acquisition programs. While Electric Warships will present new challenges beyond the requirements set for DD(X), this class of ship will field the first power system architecture on which such advanced weapon systems could be considered.

Ongoing designs for nuclear powered ships, while not incorporating electric propulsion, provide significant advances in other Electric Warship technologies. The CVNX design electrifies a wide range of ship systems presently powered by other energy sources such as steam. Most notable is the technology being developed for design options for electric aircraft launch and recovery. These massive steam and hydraulic systems in present aircraft carriers are being redesigned for the new capabilities that can only be achieved through electrification. To power all of these ship systems, CVNX will generate more than three times the electric power of the largest naval electric plant on existing carriers; enough to provide the full propulsion and balance of power needs on a cruiser-sized surface combatant. Development of militarized electric power system technologies at the higher voltage level needed to distribute this amount of power is ongoing. On the VIRGINIA SSN, solid state power conversion is being used in unprecedented applications to meet the stringent requirements of the Navy’s latest attack submarine. Overall, these ongoing developments provide the robust technology baseline that the panel has termed “Naval Electric Ship”.



### **Better Naval Electric Ships**

A sustained and significant investment in the technologies of shipboard electric generation, distribution, propulsion and auxiliary systems as well as resource management systems will be required to make the transition from Electric Ships to Electric Warships.

Electric propulsion and auxiliary systems include the electric propulsion motors, motor controllers, and the auxiliary systems that provide services to the ship and its systems. Electric propulsion provides the operating flexibility to allow power-generating resources to run at their most efficient operating point as well as control of operating points to minimize signatures. It also eliminates the mechanical shaft-line connection to prime movers, allowing physical arrangement flexibility to optimize use of the ship volume. Electric powered auxiliary equipment can eliminate the hydraulic, air and other fluid power transmission systems, while providing electric linkages for more efficient and expeditious control of these functions. The primary benefits of electric propulsion and auxiliaries are increased mobility, stealth, endurance and fuel efficiency.

Coordinated investment in electric propulsion and auxiliaries will provide dividends as the Navy pursues its integrated power vision.

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## Electric Propulsion & Auxiliaries

### Key Elements



- **Propulsion Motors**
  - Advanced Development - Higher Power Levels, Improved Power and Torque Densities, and Reduced Signatures
  - S&T - Advanced Motor Concepts, Analytical Tools, Materials, Thermal Management, and Insulation
- **Propulsion Motor Drives**
  - Advanced Development-demonstrated Drive Concepts, System Interfaces
  - S&T - Thermal Management, Insulation and Shielding Which Could Improve Power Levels, Power Density, and Signatures; Advanced Concept Development, Design/analysis Tools
- **Propulsors**
  - Advanced Development - Higher Power Levels, Maneuverability, Survivability, Efficiency and Low Signatures
  - S&T - Advanced Propulsor Concepts, Materials and Analytical Tools
- **Auxiliaries**
  - Advanced Development - Thermal Management, Intelligent Automation, Improved Load Matching and Reduced Signatures
  - S&T - Advanced System Concepts, Intelligent Systems, Materials, Thermal Management Concepts, High Force Actuators

*Necessary but not sufficient for electric warships*

## Electric Propulsion & Auxiliaries

The propulsion element of Electric Warships consists of propulsion motors, their drives and controllers, and the propulsors. Together, these devices convert power from the common electric power system into thrust to drive the ship. The adoption of integrated electric propulsion is widespread in the commercial marine market. However, these commercial systems do not meet warship requirements. Commercial market forces do not provide incentives for manufacturers to develop the compact, lightweight, and more powerful systems critical for warship performance. Additionally, commercial marine propulsion systems are not designed to provide the shock resistance and low levels of acoustic and electromagnetic signatures required for warships.

*Propulsion Motors:* Commercial propulsion motors are primarily wound field synchronous types, with induction and, recently, permanent magnet (PM) motors used in some smaller ratings. Military suppliers are currently developing new designs for warship applications, such as:

- The advanced induction motor which was selected and developed by the Navy's Integrated Power System (IPS) Program. This full scale, advanced development motor was designed and manufactured in the UK. The Royal Navy recently selected this motor design for use on their new Type 45 Destroyer. The selection was based in large part on the low costs and risks required to develop this existing prototype into a suitable production motor.
- The PM motor which potentially offers better efficiency and power density than either wound field synchronous or induction motors. PM motors are currently being offered in smaller commercial marine applications. Several

manufacturers are actively offering, or developing, PM motors for military applications in the U.S., Germany, France, and the UK.

- Superconducting motors which have become more practical due to recent advances in materials and commercial developments in cryogenics that have eliminated the need for large refrigeration plants. Superconducting motors potentially offer greater efficiency and power density than any other motor technologies. Two configurations have been proposed: alternating current (AC) synchronous and direct current (DC) homopolar. U.S. manufacturers are currently working technology demonstrations of both configurations at MW power levels.

Research should be applied in areas such as cooling and insulation techniques, and advanced materials that apply across motor types. Other S&T funding needs to be directed toward completing technology demonstrations of advanced motor technologies to enable competitive evaluations, and to improve and validate design and analysis tools. Development should be structured to achieve naval power levels, at specific power and torque density and signature goals. Advanced development programs also should continue competitive evaluation of different motor types.

*Propulsion Motor Drives:* Large numbers of high-power propulsion motor drives exist in commercial marine applications. Most of these are synchroconverter and cycloconverter configurations based on industrial drives. These configurations do not offer the performance required for warship applications. Pulse modulated drives (pulse width, pulse density, pulse frequency, etc.) previously used in smaller commercial marine applications are coming into use in larger industrial and marine applications. This change was enabled by the development of new semiconductor devices. Several configurations of these pulse modulated drives which can potentially meet Electric Warship performance requirements, are either in use or under commercial development.

Thus, the panel concluded that existing drive topologies and industrial development of semiconductor and control technologies appear to support current application developments. S&T funding should focus on technology improvements in bandwidth, control technologies, materials, thermal management, insulation, and shielding which have the potential to improve power levels, power quality, power density, reliability, and to reduce motor acoustic signatures across drive types. Further, because propulsion drives are usually provided with propulsion motors as systems, S&T funding for drives also may be required as a part of associated motor and propulsor demonstrations. In parallel, design and analysis techniques and tools should be developed and validated as required to define static and dynamic electrical interfaces of drives with common power sources and their impact on motor insulation requirements. Engineering development will be required to obtain drives to meet the requirements of warship applications at the required power levels and provide modularity that allows for graceful degradation.

*Propulsors:* Historically, conventional shaft driven propellers and water jets have been used for commercial and combatant applications. There has been recent dramatic growth in the use of azimuthing electric propulsion pods in commercial applications including cruise ships, ferries, large workboats, drill rigs, and shuttle tankers. In commercial applications, pods have demonstrated substantial improvements in space utilization, maneuverability, and overall propulsion efficiency. Water jet technology, which is best suited for high-speed applications, has also seen substantial growth. Water jets are now being offered in very high-power ratings and new configurations that potentially could broaden their application.

The panel's conclusion on propulsors is that research should focus on advanced materials and the development and validation of mechanical and hydrodynamic design tools, which are especially important to broaden the scope of, and reduce the costs for, new propulsor development. S&T funding should also be directed toward demonstrations of advanced propulsor configurations to support competitive evaluations. Advanced development efforts should focus on methods for achieving higher power levels, greater efficiency, reduced signatures, improved survivability, and enhanced maneuverability. Advanced development programs should be funded as required to support competitive evaluation.

*Propulsion Summary:* Research should focus on new materials, new design methods, and hydrodynamic analysis tools that potentially offer application across differing concepts. Technology demonstration funding should focus on advanced concepts to support their competitive evaluation. Development should leverage ongoing investments in propulsion technologies. Current programs should be funded to allow competitive evaluations. All competitive evaluations of propulsion technologies should be based on the specific warship performance requirements for their target applications. Relatively minor changes in the constraining design requirements can dramatically alter the results of propulsion component trade studies.

*Auxiliaries:* Auxiliaries include all the ship's systems not specifically included within power, propulsion or combat systems. Auxiliary systems provide support services throughout the ship including a variety of disparate equipment such as: machinery cooling systems; heating, ventilation and air conditioning systems; fuel and lubricant storage, purification and distribution systems; waste removal systems; fire/flooding detection and containment systems; hull machinery including steering gear, winches, cranes and elevators; and crew support systems including laundry, personal hygiene and food service systems. Auxiliaries also include the associated control and automation systems. The evolution to Electric Warships provides a variety of opportunities to not only improve existing auxiliary services, but also to provide new services that extend beyond the warship to the Electric Naval Force.

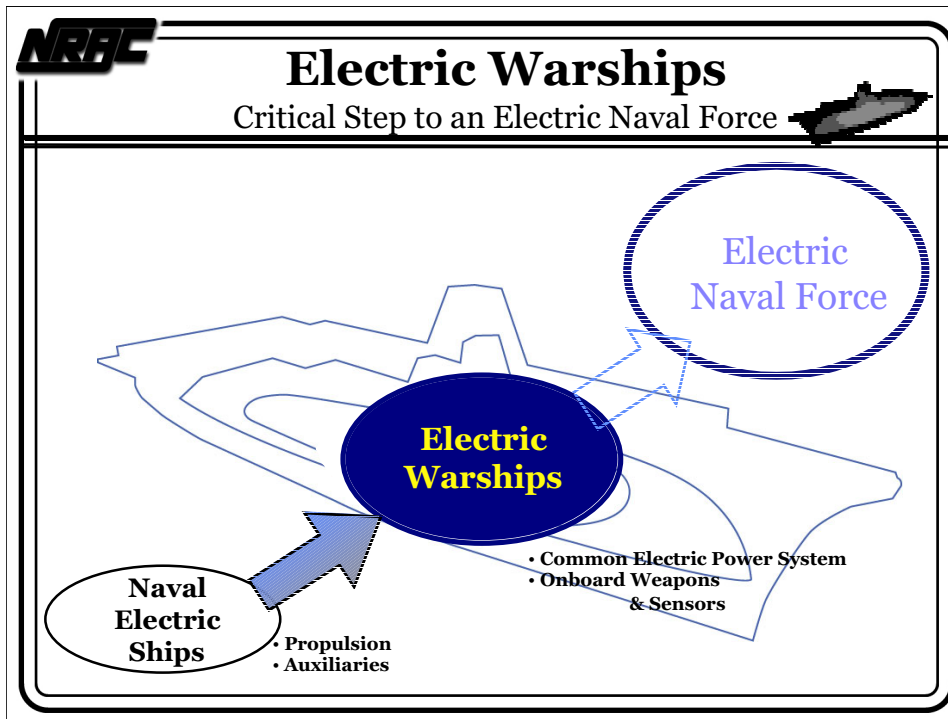
Specific areas for improvement that should be addressed by S&T efforts include the following:

- At the high electric power levels envisioned for the Electric Warship, waste heat loads will far exceed current platforms experience. Up to 28 MW of

waste heat is projected for a CG class ship. S&T funding is recommended for new equipment cooling and platform thermal management technologies and interface standards. Technologies that would permit utilization of low-grade heat are also recommended for study.

- A goal for Electric Warships is the elimination of air, hydraulic, and steam powered systems for almost all applications. The replacement of steam aircraft catapults with electric catapults on CVNX demonstrates the possibilities and benefits of these new technologies. Electrification offers the opportunity for reduced maintenance and life cycle costs, improved reliability, and improved control and automation. S&T funding is recommended for development of very high force electric actuators, and improved control of electrically powered auxiliaries for greater efficiency, speed and precision as well as for reduced signatures.
- The adoption of the Common Electric Power System allows flexibility in managing and reconfiguring shipboard power distribution for both normal operations and for recovery from fire, flooding, weapons effects, and other types of failures and damage. The increased reliability of electric auxiliaries promotes the introduction of enhanced controls, including condition monitoring, for reductions in watch-keeping requirements. Highly advanced control system development is ongoing in the industrial, commercial marine, and Navy warship arenas. Commercial developments in this area can often be directly applied to warships. S&T funding should be limited to new technologies, or application of existing technologies, that directly address unique warship requirements.

*Auxiliaries Summary:* Research should focus on new technologies, materials, design methods, and analytical tools, which could offer broad application across differing concepts. Consideration should be given to new platform auxiliary systems that would support offboard assets in an expanded Electric Naval Force environment. S&T funding should also focus on: (1) platform thermal management, (2) development of electric actuators, (3) other electric alternatives to replace the remaining hydraulic, air, or steam powered auxiliaries, and (4) the development of new control concepts that take advantage of all-electric technology. Technology demonstrations should be funded for advanced concepts as required to support their competitive evaluation. Advanced development should leverage commercial and continue ongoing Navy investments directed toward all-electric auxiliary systems.



### **Electric Warships – Critical Step to an Electric Naval Force**

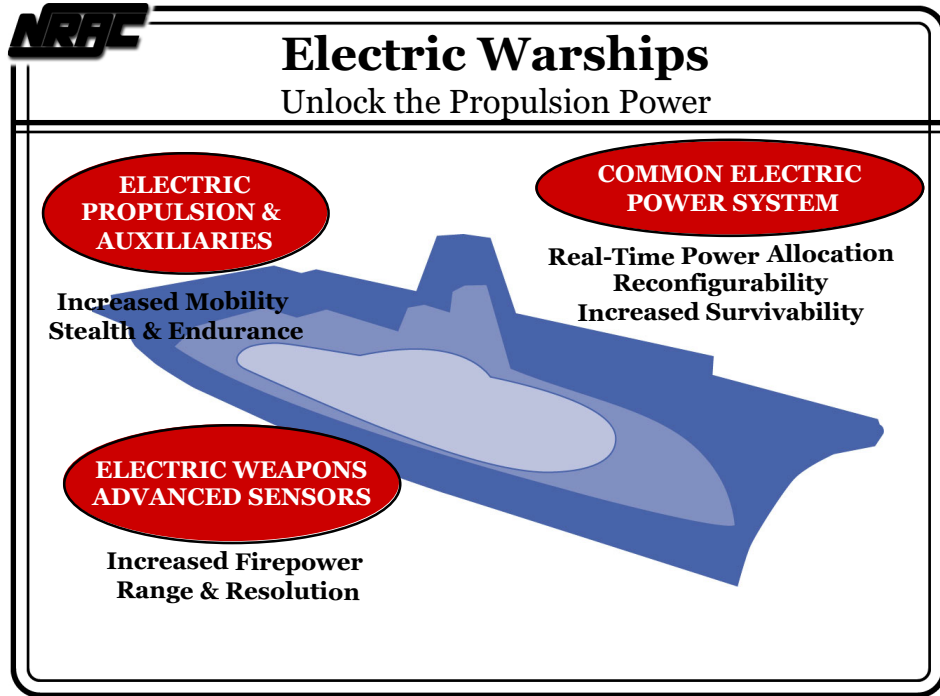
Electric Warships represent an evolution of technology that is being developed and applied in emerging naval electric ships today—LHD8, CVNX, VIRGINIA SSN and DD(X). They also represent a revolution in that they make the propulsion power available for high-power electric weapons and advanced sensors. Each weapon and sensor system has available the full resources of all the generating, energy storage, and pulse power capabilities of the Common Electric Power System. Navy Electric Warships of the future will have electric propulsion systems, auxiliary systems, launchers, sensors, countermeasures and, ultimately, high-power weapons that, coupled with low self-signatures, will permit detection and engagement of the enemy far outside the envelope for counterattack.

The Electric Warship concept builds on an open architecture based on a common system of electric power generation and distribution for propulsion, ship service, combat, and weapons loads—all coordinated and integrated by an overlying power management system. This Common Electric Power System architecture and its integrated resource management and control system will provide for real-time coordination, optimization and reconfiguration of all energy producing and consuming weapons, engineering, propulsion, combat system, and offboard assets under both normal and casualty conditions, while minimizing both installed power resources and fuel consumption.

Automated damage control and condition monitoring systems, enabled by local compartment sensors, advanced reasoning algorithms, and remotely actuated hardware, will provide ship-wide compartment integrity and status awareness. These advances can lead to substantial reduction in crew size when optimizing manning for operational, battle and damage control requirements. Watchstanding

and monitoring workload will be reduced. Electrically based propulsion and power system architectures also optimize the use of the internal volume of the ship, allowing increases in mission payload and habitability. A significant side benefit of the optimizations is the increased quality of service for Sailors.

Electric Warships integrate all ship and mission systems through a Common Electric Power System, thus making the full resources of all the generating, energy storage, and pulse power capability of the Common Electric Power System available to best support mission priorities.



### **Electric Warships – Unlock the Propulsion Power**

The Common Electric Power System with electricity as the primary medium of power generation, transport, control, and application throughout the ship, combined with high-power weapons and sensors is the only affordable way to achieve the warfighting capabilities necessary for the superior future Naval force. The Common Electric Power System is comprised of all elements of power generation (engine-generators, energy storage, fuel cells, etc.), transmission and distribution (electric power cables, bus duct, switchgear, etc.), power conversion (transformers, converters, inverters, etc.) that condition power to loads, as well as a distributed real-time control system to manage this system to maximize mission capability under all conditions. This system provides for increased survivability using real-time power allocation and rapid power system reconfigurability. The Common Electric Power System is the essential “heart and lifeblood” of an Electric Warship.

Electric weapons and advanced sensors will provide the superior warfighting capability of the Electric Warship. These include emerging EM guns that vastly increase range and firepower for land attack, high-power radars which provide very long range and high resolution target tracking, and lasers and microwave projectors which provide directed energy on targets. The tens of MWs required by these systems will be provided by diversion of propulsion power via the Common Electric Power System. The increased firepower, range, and resolution capabilities of these high-power electric weapons and sensors would be unaffordable if each required its own power source.

At this point in the evolution of the Electric Warship concept, the Panel characterized a “chicken or the egg” dilemma. As discussed, many of the advanced

weapons and sensors are not available today and have very large power requirements that make them difficult to justify as stand-alone systems. Similarly it may seem difficult to justify the investment necessary to provide the Common Electric Power System without the availability of advanced weapons and sensors. The Panel decided that the most reasonable course is to invest in the Common Electric Power System which will then let advanced weapon and sensor candidates be judged and adopted based on their impact to warfighting capabilities rather than their power supply requirements. Although several candidates are discussed in this report, the panel strongly believes that the availability of the Common Electric Power System will engender many new candidate concepts for affordably enhancing warfighting capabilities.





## Common Electric Power System

### Key Elements



- **Generation and Energy Storage**
  - Advanced Development - Power Density, Signatures, and Fuel Efficiency
  - S&T - Alternate Sources (e.g. Fuel Cells), Pulse Power Capability for Electric Weapons and Sensors
- **Power Distribution and Conversion**
  - Advanced Development - Power Quality and Fault Tolerance
  - S&T - Stability and Power Density
- **Resource Management and System Reconfiguration**
  - Advanced Development - Reconfiguration of Energy Supply and Distribution System for Fight-through Capability
  - S&T - High Peak Power/pulse Power Management and Stability

*Essential for electric warships*

## Electric Power System

The heart of the Electric Warship is the Common Electric Power System which generates, distributes and manages the allocation of power resources to all Electric Warship systems including the advanced sensors and weapons. The timeline and priorities for investment in Common Electric Power System technologies should be set according to the potential benefit to the Fleet warfighting capabilities. Many of the generation, distribution and resource management technologies may be made available as upgrades or forward fits to currently planned shipbuilding and conversion programs. Incorporating these technologies at the earliest opportunity will hasten the evolution of the Fleet toward Electric Warship capabilities.

The major subsystems that follow comprise the Common Electric Power System and will require investment.

*Generation and Energy Storage:* Power generation includes all those technologies that convert fuel into electrical power. Example technologies include advanced fuel cells, advanced high-power density generators, and the ancillary technologies required for their operation in an electric warship (e.g., fuel cell reformers and intensive thermal management). The goals for power generation are increased efficiency, increased power density, low signature and pulsed-power capability.

Energy storage is required for power interruption ride-through, pulsed-load demands, offboard asset powering, enhanced system dynamic resiliency, and recovery from “dark ship” situations. Technology options for energy storage include advanced batteries, flywheels, capacitors, and superconducting magnetic energy storage. Goals for energy storage technologies are increased power and energy

density, increased reliability and endurance, high discharge rate, and interfaces for insertion into an open architecture power system.

*Power Distribution and Conversion:* The power distribution system transmits and conditions the electric power from all generation and energy storage resources for use by all loads. Power distribution and conversion includes those technologies and system concepts that enable efficient and dependable delivery of electric power to mission critical systems including propulsion, sensors, weapons, ship's service and auxiliary support functions. Advanced system concepts for distribution and power management must be embodied in an open architecture system that accepts future technology insertion and provides dynamic reconfiguration of power distribution based on ship conditions and mission priorities.

- Passive component technologies include medium voltage switchgear, disconnect and transfer switches, circuit breakers and advanced transformers (e.g. high frequency and superconducting). Goals for passive component technologies are reduced size, weight and cost.
- Active component technologies include advanced solid-state power converters/inverters, circuit breakers, and motor controllers. Goals for active technologies are high power quality, fast switching and response, high efficiency, stability and power density.

*Resource Management and System Reconfiguration:* The resource management and control system must be capable of real-time coordination, optimization, and reconfiguration of all energy sources and loads including engineering, propulsion and combat system functions, under both normal and casualty conditions. The resource management system must be fault tolerant and robust, using hierarchical combinations of centralized and distributed intelligence for protection and control. Electrical reconfigurability, remote sensing, system performance monitoring, and information processing will provide total ship system status and conditions awareness to the power system control package and will enable automated rapid response to casualties and transient events.

Electric power system reconfigurability makes possible rapid shifts of large fractions of ships power for future electrically powered sensors, weapons (such as rail guns and lasers), and other high peak power, mission critical equipment (such as electric aircraft catapults). The Common Electric Power System will include adequate control capability to manage stability and other system constraints during the enormous power transfers required by high-powered weapons and sensor systems (which may involve up to 100% of the propulsion power being quickly shifted to weapons power and back again to propulsion, and could total to 100 MW or more). Furthermore, reconfigurability will be used to achieve stealthier operation by managing source and distribution system signature contributions to minimize acoustic, electromagnetic, and/or thermal signature in accordance with critical warfighting mission scenarios.

- Reactive reconfigurability of power system resources will prevent damage propagation outside of the primary affected zone, and support rapid recovery of surviving mission loads within the affected zone thus preserving maximum warfighting capability. Automated power systems triage will be performed within the context of the operational situation (e.g. warfighting, shore support, Theater Ballistic Missile Defense (TBMD), etc.) and mission priorities. Damage control and condition monitoring systems will incorporate new types of sensing, sensor arrays, and embedded sensing.
- Predictive reconfiguration encompasses methods for the real-time determination of the targeted area for a detected incoming threat, and the corresponding activation of dynamic reconfiguration to mitigate probable post-strike electric power system interruptions. The control system will use integrated sensors and existing ship system information networks to compose a reporting infrastructure that will be used to predict power system battle damage and cascading failures, and other ship casualty conditions, increasing Electric Warship warfighting response. Forecasting and responding to system failures (e.g. predictive reconfiguration) will ensure that failures and abnormal conditions will not surprise the power system and thus the “fight-through” capability of reconfigured mission critical resources will be significantly increased.

In summary, Resource Management and System Reconfiguration encompasses the automation and control required to provide the detection, diagnostics, and mission optimization response to different power system stresses, battle damage, anomalies, and failures. It also includes the development, analysis, modeling, and tradeoffs of new system concepts and architectures to maximize total ship warfighting performance within imposed cost constraints.

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## Onboard Electric Weapons & Sensors

### Key Elements



- **Electric Weapons**
  - Advanced Development – HPM Active Denial Capability
  - S&T – HPM Anti-Missile Self Defense, High Power Electric Lasers, EM Gun Systems
- **Sensors**
  - Advanced Development – Increased Radar Range and Resolution
  - S&T – Wide Band Gap Material RF Semiconductors, Thermal Management
- **Launchers**
  - Advanced Development – EMALS & EARS for CVNX
  - S&T – Launchers for Torpedoes, Countermeasures, U-Vehicles/Systems

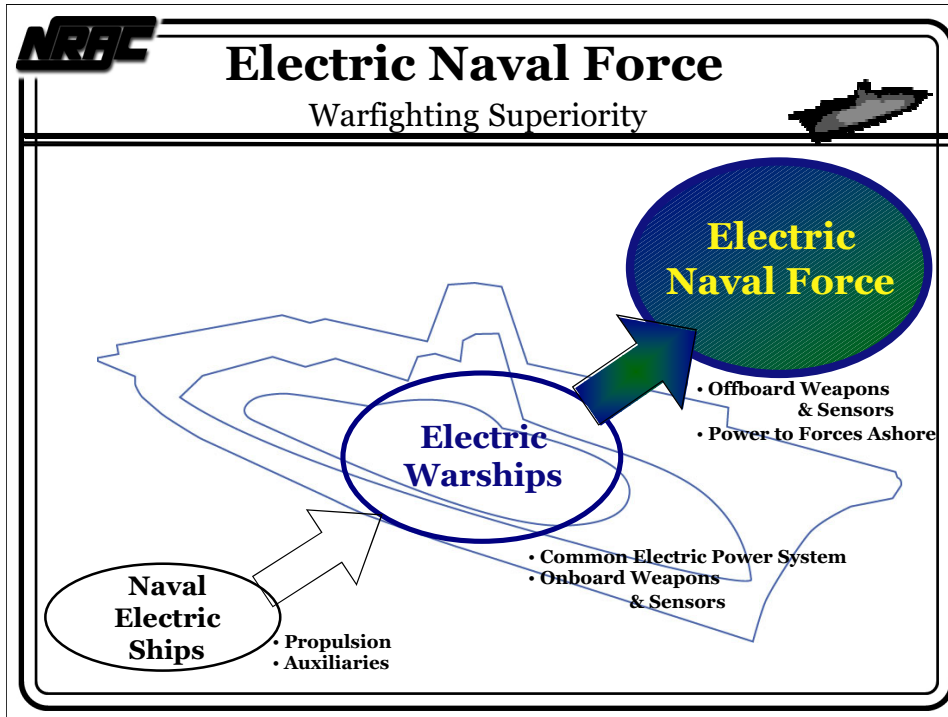
*Justification for electric warships*

## Onboard Electric Weapons & Sensors

Electric weapons, including EM guns, lasers and microwave projectors, as well as high-power radars, dynamic armor, and EM launchers provide compelling capability for the future naval force. In addition to the high-density energy storage and pulse power capability covered in the power system architecture section, these systems must also be developed. At this time, each of these systems continues to require significant S&T investment. The Army is developing EM and electro-thermal guns, the Air Force is developing active denial and high-power microwave systems, and the Ballistic Missile Defense Organization (BMDO) is developing high-powered radar—all these efforts should be leveraged. However, naval applications are unique within the Department of Defense (DOD) and the availability of tens to hundreds of MWs of electric power on Electric Warships provides unparalleled opportunities for implementing these new warfighting technologies. Leveraging ongoing S&T efforts in other agencies and services for basic technology, the Navy should initiate focused programs to develop robust weapon systems—repeatable, reliable, affordable and realizable approaches.

Thermal management must be addressed, in particular in EM guns, high-power radars, high-power microwave (HPM) and lasers. Long life barrels for rail guns, switches and coils for coil guns, and high acceleration, high payload fraction, smart projectiles are key to successful electromagnetic gun weaponization. Lethality effects against airborne threats must be addressed for both microwaves and lasers. Robust solutions are needed to address the complexity and frailty of both lasers and microwaves. Wide band gap material, radio frequency semiconductors and fast discharge capacitors/switches are examples of critical enabling research to support the full capabilities envisioned for these systems.

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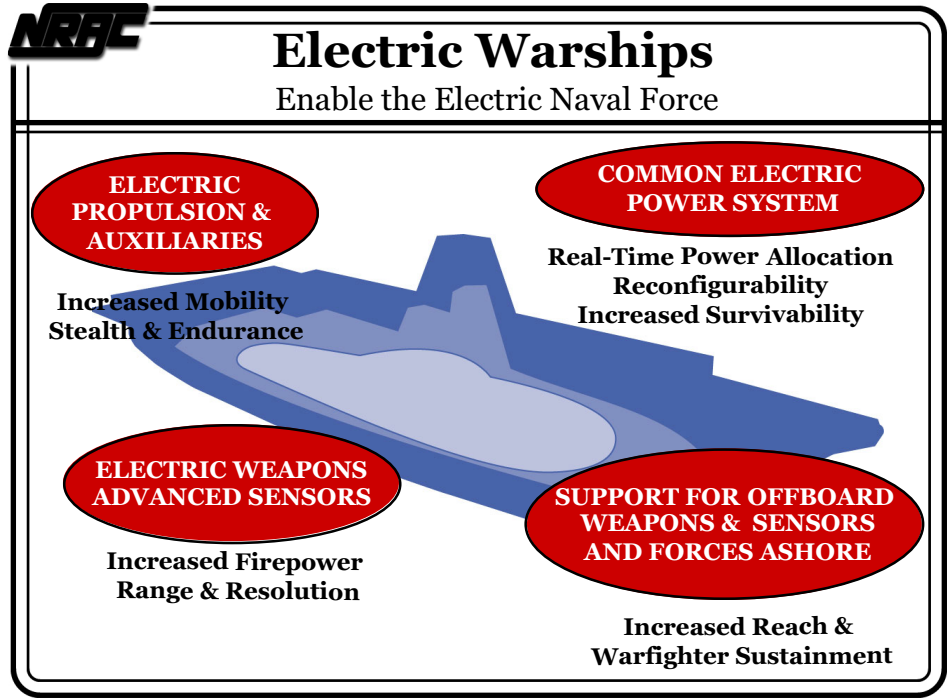


### Electric Naval Force

The challenging naval missions of the future can best be accomplished with a superior Electric Naval Force. The foundations of an Electric Naval Force are the Electric Warships, where all power for high-power weapons, advanced sensors, propulsion, and other essential ship mission capabilities is available electrically and on demand from a Common Electric Power System. Advanced methods of exporting Electric Warship power to support offboard unmanned assets and forces ashore will bring about the realization of the superior Electric Naval Force.

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**Electric Warships**

The four key technology thrusts which will provide the power intensive, technically superior capabilities of the 21st century Naval force are shown in this graphic of Electric Warships. The Electric Naval Force of the future will include electrically powered Marine Corps combat vehicles and weapons, as well as unmanned surface, subsurface, air and land assets for passive and active warfighting. The power resources of the Electric Warship will provide continuous electric supply or rapid electrical recharging of these offboard assets increasing their firepower, range, and endurance, while reducing their logistics burden—effectively extending the reach and endurance of the Electric Naval Force.

Electric Warships utilizing a Common Electric Power System as the primary mechanism for power transport, control, and application throughout the ship and offboard are the only way to achieve these capabilities.

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## Offboard Electric Power

### Key Elements



- **Unmanned/Unattended Weapons & Sensors**
  - Advanced Development – Higher Energy & Power Density Systems and Batteries
  - S&T – Fuel Cells, Wireless Power Transmission
- **Individual Marines**
  - Advanced Development – Higher Energy & Power Density Systems and Batteries
  - S&T – Small, Light Weight Fuel Cells
- **Hybrid Electric Combat Vehicle Propulsion & Weapons**
  - Advanced Development – Active Denial High Power Microwave, High Power Density Systems, Hybrid Electric Drives
  - S&T – Weapons Power Systems, Lasers, Anti-Missile High Power Microwave, Wireless Power Transmission

*Realization of electric naval force*

### Offboard Electric Power

*Unmanned/Unattended Weapons & Sensors:* Expanded mission capabilities for the ship and for forces ashore are provided by unmanned and unattended weapons and sensors. Today, batteries are the critical enabling technology for such electric systems, but alternate energy sources such as fuel cells are needed to increase range and endurance.

The ability to transmit electric energy to remote users, such as Marines or unmanned aerial vehicles would provide a true leap ahead capability. (During the post 1973 energy crisis, systems were investigated and found to be feasible in which a solar panel in space generated electricity that was to be transmitted at microwave frequencies to a receiver on the ground.) The feasibility of transmitting energy from an Electric Warship to electrically powered unmanned vehicles or Marines ashore, providing greatly extended endurance, should be carefully investigated.

*Personal Power Systems:* Marines of the future will require increasing levels of electric power for personal communications, sensors, weapons and protection. Personal power systems should be developed within the overall context of an integrated naval force. For instance, personal power for Marines could be provided by rechargeable batteries, which are receiving large investments by the commercial personal computer and cell phone industries, if hybrid electric combat vehicles provided the capability for rapid recharge of the batteries. The Electric Warship could produce hydrogen, making fuel cells more attractive for both combat vehicles and Marines. Hydrogen burning microturbines offer yet another alternative for personal power systems.

*Hybrid Electric Combat Vehicles:* Electric weapons, drives, auxiliaries and actuators, such as active suspensions, provide potential leap ahead capability for

Marine Corps Combat Vehicles. DON should leverage significant investment by the commercial sector and the Army for Marine Corps applications. Compact, high efficiency engine/generators; energy storage, both batteries and flywheels; high temperature (100°C) power electronics; wheel motors and active suspensions; all require development, integration and demonstration for specific Marine Corps systems.

Optimization of power distribution, control systems and thermal management are keys to success. Hybrid electric power could significantly improve the performance of amphibious vehicles by providing high peak power for offshore propulsion and high efficiency for onshore propulsion. Finally, pulse power should be developed and integrated into the hybrid power system to enable the introduction of high-power weapons for the combat vehicles.



# Common Electric Power System

## Detailed Assessment

	<b>Research</b> Impact/Risk/Cost	<b>Technology Demonstration</b> Impact/Risk/Cost	<b>Advanced Development</b> Impact/Risk/Cost
<b>Generation Systems</b>	H / H / H Propulsion Fuel Cell	H / M / H Advanced Generator H / M / H Ship's Service Fuel Cell	H / L / M Turbine Generator
<b>Energy Storage</b>	L / H / H Super Conducting Magnetic Energy Storage	L / M / M Super Capacitors H/M/M Advanced Batteries	L/L/M Batteries L/L/L Flywheels L/L/L Redox
<b>Pulse Power</b>	H / H / M High Action Switch H/H/M Pulsed Capacitors (10 J/gm)	H / M / M Compulsators H / M/M Pulsed Capacitors (3 J/gm)	H/L/L Pulsed Flywheel

### Electric Power System – Detailed Assessment

This table presents a more detailed assessment of specific candidate technologies highlighted by the panel as being relevant to the Naval Electric Power System. Similar tables for Electric Propulsion and Auxiliaries, Onboard Electric Weapons and Sensors and Offboard Electric Power are included in Appendix D.

These technologies are arranged from left-to-right, in order of increasing technical maturity as being candidates for Research, Technology Demonstration, or Advanced Development, respectively. Each technology candidate was rated on the basis of impact on Electric Warship capabilities, development risk and development cost. Ratings were subjectively assigned as high, medium, or low for each of these criteria. Cost was based on the investment required to mature the technology through the transition out of advanced development. High cost is greater than \$50M, medium cost is \$10M to \$50M, and low cost is less than \$10M.

These tables should not be considered exhaustive in any sense. The panel is well aware that many workshops and other gatherings of experts have identified a wide range of technologies that may be applicable to the Electric Warship. Recent examples include DoD workshops on Electric Power Technology and Electric Armaments and Protection, the Technology Thrust Working Group for the Electric Warship Strategy Task Force, and a planned Electromagnetic Launch Workshop cosponsored by Program Executive Officer for Surface Strike (PEO (S)) and ONR. The panel encourages the Navy to evaluate technology needs and candidates from all sources and through a rigorous evaluation process, determine that set of investments which best fits the needs and schedule of the Electric Warship development effort.

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## Crosscutting Concerns

Electric Warships/Electric Naval Force



- Systems Engineering
  - Validated models
  - Configuration control
  - Interface definition
- Thermal Management
- Health/Safety Standards for Low Frequency Magnetic Fields (Draft IEEE 1555 standard)
- Military/Industrial/Academic infrastructure

### **Crosscutting Concerns**

*Models:* There is a critical need for physics based models, validated through experimentation, to analyze transient performance and system stability as well as to optimize the performance of the overall power and weapon systems. Weapons operation and faults are transient events whose impact on the power system is complex. Physics based models of components, subsystems and systems should be developed and validated against existing systems and technologies as well as future experiments. It is essential that these models not be idealized to the extent that they do not give useful results-the level of detail in the models must be appropriate to the issues being addressed.

DON should own these models and must pay for their development. These models will form the basis for the engineering trades and analysis parts of simulation based acquisition and are crucial to evaluating and optimizing the technologies and architectures as well as establishing commonality of approach. These models, if properly designed, can also be used directly in the control systems for the components, subsystems and systems.

*Thermal Management:* Thermal management is a critical technology for any electric power system-the need is even more extreme for high-power density naval systems. Thermal management is the single issue with the most impact on reliability and as such, deserves attention in its own right. Hierarchical thermal management starts with electric power components which generate heat. They must be protected so that they remain within their respective thermal ratings. The next level of the hierarchy is collection of the waste heat within systems or sub-systems. Finally, the heat must be rejected to the air or seawater. Proper thermal management is crucial to achieving high overall systems power density. At each step, the need exists for

advanced materials and techniques as well as accurate models to minimize the production of waste heat and to minimize its negative impact on overall system power density and reliability.

In the past, there has been little information on the health and safety implications of exposure of humans to low frequency magnetic fields such as those associated with electric power systems and electromechanical energy converters. Much needed guidance on health/safety issues of low frequency magnetic fields now exists as Draft IEEE Standard 1555, which will be adopted by DoD. This standard should be applied early in the development of the electric technologies discussed in this report in order to minimize the effort to make them safe for naval personnel as they are introduced into the Electric Naval Force.

Finally there are a number of resource issues that must be addressed in order to successfully realize the benefits of the Electric Naval Force.

The Navy and Marine Corps must address the training of Sailors and Marines to operate and repair the complex electric systems that will provide the technical superiority for the force. Specialized test facilities will be required and should be designed to be flexible rather than dedicated to specific programs.

The emerging marine electric industrial base is largely European at present. There exists an embryonic U.S. industrial base which should be nurtured as investment is made in technology development.

Similar attention must be paid to re-establishing the electric power engineering academic base that will provide the engineers to design and develop electric naval systems and naval architecture schools must incorporate marine electric technologies into their curricula for the Navy to derive the benefit of design flexibility afforded by the transition to Electric Warships.



## Conclusions



- **Navy on the path to ELECTRIC SHIPS**
- **ELECTRIC WARSHIPS add flexible real-time power allocation**
- **Electric weapons and advanced sensors provide the technically superior ELECTRIC NAVAL FORCE**

### Conclusions

Given the commitment to LHD8, DD(X), CVNX and VIRGINIA SSN, the Navy will derive the benefits of electric ships—that is, ships with electric propulsion and electric auxiliaries. Those benefits, confirmed by commercial marine experience, include reduced operating costs, improved reliability, and compatibility with automated monitoring and control.

Making the propulsion power available to combat systems will create Electric Warships where the platform energy resources are available to be allocated in real-time to meet mission needs. The electric weapons and advanced sensors that are the justification for this evolution to Electric Warships will provide the technically superior Electric Naval Force necessary to meet the challenges of the 21<sup>st</sup> century.

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## Conclusions (cont'd.)



- **Navy not yet fully committed to ELECTRIC WARSHIPS**
- **Common technology base essential for ELECTRIC NAVAL FORCE**
- **No technology development strategy exists for the ELECTRIC NAVAL FORCE**

### Conclusions (cont.)

Although well on the way to realizing electric ships, there is not yet a corporate commitment to the evolution to Electric Warships. Throughout the Navy, the panel was gratified to find groups working on Electric Warship concepts and these should be encouraged and consolidated by a clearly articulated DON vision of the evolution from electric ships to Electric Warships.

There is concern that the lack of a common technology base among the various naval platforms that will make up the Electric Naval Force will result in excessive costs and risks, which could prevent the ultimate realization of such a force. This is not to say that submarines should necessarily use the same propulsion motors as surface combatants, but that all platforms should coordinate the development and application of common models, design tools, manufacturing methods, advanced materials, devices, components, subsystems, systems and control hardware and software where appropriate. Properly applied, this approach will substantially reduce risk, maximize cost benefits and reduce training and logistics burdens.

The panel is also concerned about the present piecemeal approach to the development of technologies critical to the successful evolution of an Electric Naval Force. Constrained resources make it essential for DON to lay out a strategy that identifies a hierarchy of critical Electric Warship/Electric Naval Force technologies and apportions resources accordingly. This effort should clearly identify where DON will rely on commercial technologies or collaboration with other services, government departments or foreign navies and where it will depend solely upon its own resources. Since the commercial and collaborative resources are beyond direct

DON control they must be closely monitored and the investment strategy updated accordingly.



## Recommendations



- **Establish centralized responsibility for implementing DON commitment to ELECTRIC WARSHIPS**
- **Develop balanced technology investment strategy for the ELECTRIC NAVAL FORCE**

### **Recommendations**

In order to ensure the realization of both the warfighting and cost saving benefits of Electric Warships, the panel recommends that DON establish a centralized responsibility for implementing its commitment to their development. The panel applauds the establishment of an Electric Warship Strategy Task Force as a critical first step toward accomplishing this recommendation.

It is equally important for DON to develop, articulate and implement a balanced technology investment strategy to ensure the realization of its vision of the technically superior Electric Naval Force to meet the challenging requirements of the 21<sup>st</sup> century.

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## Electric Naval Force

If Navy Commits Now...



- **Immediate benefits:**
  - Fuel efficiency
  - Endurance
  - Range
  - Crew workload
  - Maintenance
  - Graceful degradation
  - Physical arrangement flexibility
- **Future benefits:**
  - Superior warfighting upgrades

### Electric Naval Force

There is no downside to DON commitment to Electric Warships/Electric Naval Force. The realization of reduced operating costs, improved performance, automated monitoring and control, “fight-through” ability and more flexible platform layouts will accrue immediately. More importantly, unlocking the propulsion power will “open the door” for electric weapons and advanced sensors which are the true justification for Electric Warships. Finally, the availability of Electric Warship power for offboard sensors, weapons and forces ashore will enable the realization of the Electric Naval Force.

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## The Alternative

What Happens If We Don't...



*Disconnected from Industrial Base*



*Warfighting Upgrades Unaffordable*

~~*Superior Naval Force*~~

*"Transformation is not a goal for tomorrow, but an endeavor that must be embraced in earnest today"*

Quadrennial Defense Review, Sept. 2001

### The Alternative

On the other hand, failure to make the necessary commitment to Electric Warship / Electric Naval Force, means that continued DON reliance on traditional technologies will result in a growing mismatch with the industrial base as it evolves toward electric based technologies. This lack of industrial base in traditional naval technologies, combined with the lack of flexibility for technology insertion offered by traditional naval platforms, will result in warfighting upgrades becoming increasingly unaffordable. This will ultimately lead to the inability to affordably maintain a superior Naval force.

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Appendix A  
Terms of Reference  
Roadmap to an Electric Naval Force

**BACKGROUND:**

Naval forces are on the verge of a revolution in the distribution, control and utilization of power onboard weapons platforms. All-electric ships, boats and combat vehicles offer the promise of improved performance, increased versatility and lower cost of ownership. In order to take full advantage of the opportunities offered by integrated electric power systems, a power system architecture that will facilitate flexibility in operation, rapid recovery from damage, ease of maintenance and ready integration of new technologies as they become available is essential.

**SPECIFIC TASKING:**

- Review and assess recent trends and developments in the application of electric power to naval platforms as well as weapons and auxiliary systems.
- Recommend a power system architecture for optimum long-term exploitation of the benefits of integrated power systems for Naval forces.
- Recommend a science and technology roadmap for the development of an integrated electric Naval force and identify possible roadblocks to its successful realization.

Study Sponsor: Assistant Secretary of the Navy (Research, Development and Acquisition)

Study Administrator: Chief of Naval Research and NRAC Executive Director

Study Coordinator: Deputy Commander for Integrated Warfare Systems, Naval Sea Systems Command

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Appendix B  
Panel Membership  
Roadmap to an Electric Naval Force

**Chairperson**

Prof. William F. Weldon \* ..... Professor Emeritus, Univ. of Texas at Austin

**Vice Chairperson**

Mr. Peter A. Gale \* ..... J.J. McMullen Associates, Inc.

Mr. R. Michael Adair ..... GD Bath Iron Works  
Mr. Mark Adamiak..... GE Power Management  
Mr. Clifford L. Allen, P.E..... Ingalls Shipbuilding, Inc.  
Dr. Robert W. Ashton ..... Naval Postgraduate School  
Mr. Charles H. Brown, Jr. .... SYNTEK Technologies Corporation  
RADM Lewis A. Felton, USN (Ret)..... Private Consultant  
Dr. Robert Fischl..... F&H Applied Science Associates, Inc.  
Mr. John H. Gully ..... Science Applications International Corporation  
  
Dr. Eric Horvitz \* ..... Microsoft Research  
Dr. James E. Hubbard, Jr. \* ..... IproVica  
VADM E.R. “Rudy” Kohn, Jr. USN (Ret) \*\* ..... Private Consultant  
Mr. Maxwell Mulholland..... America Superconductor  
Dr. William A. Neal, M.D. \* ..... West Virginia University  
CDR Paul T. Norton, RN (Ret)..... Alstom Power Conversion Ltd  
LtGen Keith A. Smith, USMCR (Ret) \*\* ..... Private Consultant  
Dr. Jason Stamp..... Sandia National Laboratories  
Mr. Howard Stevens ..... Anteon Corporation  
RADM John T. Tozzi, USCG (Ret)..... SYNTEK Technologies Corporation  
Mr. Timothy J. Winter..... Northrop Grumman Corporation  
CDR Stuart Young, RN ..... Defence Procurement Agency, MoD

**Study Coordinator**

RADM George R. Yount, USN ..... Naval Sea Systems Command  
Mr. David Clayton..... Naval Sea Systems Command

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CAPT Dennis L. Ryan, III, USN (Ret.) ..... ONR  
CAPT Leo G. Dominique, USN (Ret.)..... Noesis, Inc.  
CDR Joe S. Konicki, USN ..... Naval Sea Systems Command

\* NRAC Committee Member | \*\* NRAC Associate Member

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Appendix C  
List of Briefs, Field Trips and Reports  
Roadmap to an Electric Naval Force

BRIEFING	NAME	ORGANIZATION
<b>First Meeting – 24-25 July 2001</b>		
Discussion of Expectations from Study Sponsor	RADM George Yount, USN	NAVSEA
Pulsed Power Applications Ship Power System Implications	Mr. Alan Walls	CNA
Advanced Electromagnetic Aircraft Launch System (EMALS)	Mr. Dick Bushway	NAVAIR
LHD-8	CDR Norbert Doerry, USN	NAVSEA PMS 377RB
Technology Assessment for Surface Navy Radar Roadmap	Dr. Wayne Martin	ONR
USCGC Healy's Integrated Power Plant	Mr. Larry Wilkerson,	USCG Engineering Logistics
Strategic Studies Group	Mr. Mike Stumborg	SSG
Long Range Coilgun for Naval Fire Support	Dr. Bob Turman,	Sandia National Laboratories
High Power Microwave	Dr. Preston Grounds	NRL
<b>Second Meeting – 8-9 August 2001</b>		
Navy Organizational Structure Relating to Electric Warship	Mr. Randy Reeves	NAVSEA 05Z
CVX Power Systems	Mr. Bill Levin	NAVSEA
VIRGINIA Class Submarine	Mr. Bill Levin	NAVSEA
Ship Survivability Overview	Dr. Fred J. Fisch	NAVSEA
Naval Power Systems	Mr. John Sofia	NSWC Code 81
Ship Service Power System Architecture	Mr. Dave Clayton	NAVSEA 05Z3
Stability in Naval Electric Power Systems	Mr. Mohamed Belkhayat	Newport News Shipbuilding
Electric Ship and Marine Engineering Development Programmes	LCDR Toby Drywood, RN	British Royal Navy
Integrated Power Systems	Mr. Mike Collins	PEO(S) PMS 510
IPS – Full Scale Advanced Development Test Results	Mr. Henry Hegner	PEO(S) PMS 510D
Electric Warship NAVSEA Perspective	Mr. Randy Reeves	NAVSEA 05Z
Naval Fuel Cell Development Center	Mr. Donald Hoffman	NAVSEA

<b>Third Meeting – 24-25 August 2001</b>		
GTS Infinity	CDR Paul Norton, RN	Alstom
Infinity Cruise Vessel Manning Summary		
Millennium: the first gas turbo-electric cruise liner		
Podded Propulsion Goes Beyond the Cruise Realm	David Tinsley	Maritime Reporter & Engineering
Navy High Energy Laser Program	Dr. Eli Zimet	ONR
<b>Fourth meeting – 11-12 September 2001</b>		
All Electric Ship Concept Assessment Studies	Mr. Jeff Peters	NSWC Carderock
USS COLE Damage Assessment/Lessons Learned	Mr. Rich Wiersteiner	NAVSEA PMS 400D
Electric Ship and Combat Vehicle FNC	Mr. Scott Littlefield	ONR
Early Electric Ship Justification	Mr. C. Krolick	NRL
Electric Technology Overview	Dr. Albert Tucker	ONR
Electric Motor/Propulsion S&T	Mr. Gary Jebsen	ONR
Advanced Electrical Power Systems	Mr. Terry Ericson	ONR
CNO SSG XIX Support and SSG XVIII Rail Gun Study	Mr. Mark Bebar	NAVSEA
State of the art in Power System Protection, Control, and Communication Standards	Mr. Mark Adamiak	GE Power Management



<b>REFERENCE MATERIAL</b>	<b>AUTHOR</b>	<b>ORGANIZATION</b>
An Historical Overview of Navy Electric Drive	Timothy J. Dole, Henry N. Robey, Anteon Corporation, ETC Howard O. Stevens	
The Impact of Gun Dimensions on the Operational Effectiveness V37, No 1, Jan2001	Michael F. Stumborg	IEEE TransMag
The Operational Value of Long Range Land Attack EM Guns to Future Naval Forces	Ivan T. Luke, Jr and Michael F. Stumborg	IEEE TransMag V37, No 1, Jan2001
DD 21 Media Material – Blue Team-General Dynamics/Lockheed Martin Press Leads the Way to Navy After Next and Improves Quality of Life for sailors		
Gold Team Touts “Tradition-Breaking” DD-21 Design	Defense Daily, 11 April 2001	
Speed of the Essence for Big Boxships	Mr. Tony Gray	Lloyds List, May 17, 2001
ABB Initiative Targets Big Boxship Power Needs	Lloyds List, May 24, 2001	
A Business Case Analysis of Integrated Electric Power Systems for Naval Ships and Submarines: The Project Plan July 1999	John Birkler, Mark Arena, Isaac (Draft) Chapman, Emile Ettedgui, Ron Hess, John Schank, Denis Rushworth, Malcolm MacKinnon, James Chiesa John R. Hull, Patrick E. Phelan	RAND DRR-2108 Navy/OSD Porche, David Berger, Robert
The Cold Reality of Power		Mechanical Engineering, June 2001
IEEE P1555/D5 – Draft Standard for Safety Levels With	Subcommittee 3 of Standards	IEEE
Respect to Human Exposure to Electric and Magnetic Fields, 0 to 3 kHz	Coordinating Committee 28	
Metal Fuel Cell	Michael J. Riezenman	IEEE Spectrum, June 2001



CRS Report for Congress – Electric-Drive Propulsion for US	Ronald O’Rourke	Congressional Research Service
Navy Ships: Background and Issues for Congress	July 31, 2000	
Podded Propulsion Goes Beyond the Cruise Realm	Maritime Reporter & Engineering News	
Powering the Future with the Integrated Power System	LCDR Norbert Doerry, USN	Naval Engineers Journal, May 1996
	Henry Robey, LCDR John Amy, USN, Chester Petry	
Project Memorandum – A Review of Large Electric RAND PM-993 Navy/OSD	Motors	Emile Ettetdgui, Denis Rushworth,
and Their Power Controllers for Ship Propulsion	Isaac Porche, Malcolm MacKinnon,, Robert Chapman	October 1999
Shipboard electric power distribution: AC versus DC is not the issue, rather how much of each is the issue	LCDR J.V Amy, D.H. Clayton, R.O. Kotacka	Institute of Marine Engineers, 1998
The Electric Ship	General Electric Company, 1919	
USS NEW MEXICO (BB 40)	Fleet Reserve Association	
Why Electric Ship? - DoD Electric Armament/Protection Technology Workshop, 26-29 March 2001 (IDA)	Dr. Albert Tucker	ONR 334
DDR&E Technology Area Review & Assessment – Electric Technology Overview	Dr. Albert Tucker	ONR 334
In-Depth Review – Ship Hull, Mechanical & Electrical Systems S&T Division (Edited)	Dr. Albert Tucker	ONR 334
In-depth Review - Surface Ship Technology ONR 334	(Edited)	Mr. Jim Gagorik
Submarine HM&E S&T Overview (Edited)	Mr. Gary Jebsen	ONR 334
Submarine S&T Demonstrations – Advanced Machinery Support Systems Quiet electric Drive Project M (Edited)	Mr. Gary Jebsen	ONR 334
Electric Motor/Propulsion S&T	Mr. Gary Jebsen	ONR 334
In-depth Review - Automation for Reduced Manning	LCDR Frank Novak, USN	ONR 334

Advanced Electrical Power Systems Overview	Mr. Terry Ericson	ONR 334
In-depth Review - Advanced Electrical Power System Devices S&T	Mr. George Campisi	ONR 334
Advanced Electrical Power Systems Major Demonstrations	Mr. Steve Satzberg	ONR 334
Beyond Electric Ship (Preprint subject to revision), October 2000	CDR J.M. Newell, RN CDR S.S. Young, RN	British Royal Navy
The Electric Warship III (To be read on 16 December 1997 to Institute of Marine Engineers)	CDR C.G. Hodge, RN CDR D.J. Mattick, RN	British Royal Navy
The Electric Warship IV (To be read on 15 December 1998 to Institute of Marine Engineers)	CDR J.M. Newell, RN CDR C.G. Hodge, RN	British Royal Navy
The Electric Warship V (To be read on 14 December 1999 to Institute of Marine Engineers)	CDR C.G. Hodge, RN CDR D.J. Mattick, RN	British Royal Navy
The Electric Warship VI (To be read on 12 December 2000 to Institute of Marine Engineers)	CDR C.G. Hodge, RN CDR D.J. Mattick, RN	British Royal Navy
Turning Carbon Directly into Electricity	Lawrence Livermore National Laboratory	

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Appendix D  
Detailed Assessment of Technology Thrust Areas  
Roadmap to an Electric Naval Force

These technologies are arranged from left-to-right, in order of increasing technical maturity as being candidates for Research, Technology Demonstration, or Advanced Development, respectively. Each technology candidate was rated on the basis of impact on Electric Warship capabilities, development risk and development cost. Ratings were subjectively assigned as high, medium, or low for each of these criteria. Cost was based on the investment required to mature the technology through the transition out of advanced development. High cost is greater than \$50M, medium cost is \$10M to \$50M, and low cost is less than \$10M.

 <b>Electric Propulsion &amp; Auxiliaries</b> Detailed Assessment 			
Element	Research	Technology Demonstration	Advanced Development
Critical attributes	Impact/Risk/Cost	Impact/Risk/Cost	Impact/Risk/Cost
<b>Propulsion Motors</b> Higher Power Levels Greater Power Density Lower Signatures	<b>H / L / L</b> Advanced Motor Technologies (materials, cooling, insulation, etc)	<b>H / H / M</b> Advanced Motor Concepts	<b>H / M / H</b> Demonstrated Motor Designs
<b>Propulsion Motor Drives</b> Higher Power Levels Greater Power Density Lower Signatures RMA	<b>H / L / M</b> Advanced Drive Technologies (cooling, insulation, shielding, control techniques)	<b>H / L / L</b> Advanced drive concept development, design/analysis tools	<b>H / L / M</b> Demonstrated drive concepts, system interfaces
<b>Propulsors</b> Higher Power Levels Greater Efficiency Lower Signatures Improved Survivability Enhanced Maneuverability	<b>M / L / M</b> Advanced Propulsor Technologies (materials, analytical tools)	<b>H / M / M</b> Advanced Propulsor Concepts	<b>M / M / M</b> Demonstrated Propulsor Designs



## Electric Propulsion & Auxiliaries ( cont.) Detailed Assessment



Element Critical attributes	Research Impact/Risk/Cost	Technology Demonstration Impact/Risk/Cost	Advanced Development Impact/Risk/Cost
<b>Auxiliaries</b> -Elimination of air, hydraulic and steam machinery and actuators -Thermal Management -Automation (damage control, reduced manning) -Efficiency (load matching) -Reduced signatures	<b>M/L/M</b> Advanced Auxiliary System Technologies (Intelligent Systems, Materials, Thermal Management concepts, high force actuators)	<b>M/M/M</b> Advanced Auxiliary System Concepts (Concept EDM's)	<b>M/M/M</b> Demonstrated Auxiliary System Designs



## Common Electric Power System Detailed Assessment



	Research Impact/Risk/Cost	Technology Demonstration Impact/Risk/Cost	Advanced Development Impact/Risk/Cost
<b>Transmission</b>	<b>M / H / H</b> Superconducting Cables		<b>L / L / L</b> 15kV Shipboard Cable
<b>Circuit Protection/ Switchgear</b>	<b>L / H / H</b> Solid State	<b>M / M / M</b> Hybrid	<b>M / L / M</b> Electromechanical
<b>Power Conversion/ Conditioning</b>	<b>M / H / H</b> Superconducting Transformers	<b>M / M / M</b> Advanced Power Converters	<b>M / L / M</b> Ship Service Conversion
<b>Power Management/ System Reconfiguration</b>	<b>H / M / L</b> Predictive Reconfiguration	<b>H / M / M</b> Large Signal Stability <b>H / M / L</b> Active Stabilization	<b>H / L / L</b> Reconfig./Sys. Mgt./Prot. System <b>H / L / L</b> Comm./Control Infrastructure <b>H / L / M</b> Power Quality



## Onboard Electric Weapons & Sensors

### Detailed Assessment



<b>Power for</b>	<b>Research</b> Impact/Risk/Cost	<b>Technology Demonstration</b> Impact/Risk/Cost	<b>Advanced Development</b> Impact/Risk/Cost
<b>EM Launch &amp; Recovery</b>		<b>M/M/M</b> Torpedo, Countermeasure, U-Vehicle Launchers	<b>H/M/H</b> EMALS & EARS
<b>EM Guns</b>	<b>H/H/M</b> Guided Projectiles, Barrel Materials	<b>H/M/H</b> Land Attack/ Support of Forces Ashore/Ship Defense	
<b>High Power Radar</b>		<b>H/M/H</b> Full Capability	<b>M/M/H</b> Initial Capability
<b>High Power Microwave</b>		<b>H/M/M</b> Anti-Missile	<b>M/M/M</b> Active Denial
<b>Laser</b>	<b>H/H/H</b> Free Electron	<b>M/M/M</b> Solid State	



## Offboard Electric Power

### Detailed Assessment



<b>Power for</b>	<b>Research</b> Impact/Risk/Cost	<b>Technology Demonstration</b> Impact/Risk/Cost	<b>Advanced Development</b> Impact/Risk/Cost
<b>Unmanned/ Unattended Weapons &amp; Sensors</b>	<b>H/H/M</b> Wireless Power Transmission	<b>M/M/L</b> Application of Alternate Energy Sources	<b>M/M/M</b> Application of Advanced Batteries
<b>Individual Marines</b>		<b>H/M/M</b> Application of Alternate Energy Sources	<b>H/M/M</b> Application of Advanced Batteries
<b>Hybrid Electric Combat Vehicle Propulsion &amp; Weapons</b>	<b>H/M/M</b> Electric Weapons, Advanced Power/RF Components	<b>M/M/M</b> Advanced Power/Propulsion Subsystems	<b>H/M/M</b> Hybrid Power/Propulsion

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Appendix E  
Acronyms  
Roadmap to an Electric Naval Force

AC	Alternating Current
AFB	Air Force Base
ASN(RD&A)	Assistant Secretary of the Navy (Research, Development, and Acquisition)
BMDO	Ballistic Missile Defense Organization
C	Celsius
CAPT	Captain
CDR	Commander
CG	Cruiser, Guided Missile
CINCLANTFLT	Commander in Chief, U.S. Atlantic Fleet
CNA	Center for Naval Analysis
CNO	Chief of Naval Operations
COTS	Commercial off-the-Shelf
CVNX	Aircraft Carrier of the Future
DC	Direct Current
DD21/(x)	Next Generation Destroyer
DON	Department of the Navy
EARS	Electromagnetic Aircraft Recovery System
EM	Electromagnetic
EMALS	Electromagnetic Aircraft Launch System
ERGM	Extended Range Gun Munition
GTS	Gas Turbine Ship
H	High
HECV	Hybrid Electric Combat Vehicles
HP	Horse Power
HPM	High Power Microwave
IEEE	Institute of Electrical and Electronics Engineers
IPS	Integrated Power System
KHz	Kilohertz
L	Low
LHD8	Amphibious Ship, Landing Helicopter Dock
M	Million/Medium
MW	Megawatt

N70	Director, Warfare Integration and Assessment Division, Office of the Chief of Naval Operations
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NRAC	Naval Research Advisory Committee
NSWC	Naval Surface Warfare Center
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
PEO (S)	Program Executive Officer for Surface Strike
PM	Permanent Magnet
PMS	Program Manager Ship
RADM	Rear Admiral
RF	Radio Frequency
RN	Royal Navy
S&T	Science and Technology
SSG	Strategic Studies Group
SSN	Submarine, Nuclear Powered Attack
TBMD	Theatre Ballistic Missile Defense (Program Canceled)
TOR	Terms of Reference
U	Unmanned
UK	United Kingdom
USCG	United States Coast Guard
USCGC	United States Coast Guard Cutter
USMC	United States Marine Corps