

An hourglass-shaped graphic with a globe inside. The top bulb is dark blue, and the bottom bulb is light blue. The globe is centered in the narrow neck of the hourglass. The top bulb has a dark blue cap. The bottom bulb has a light blue cap.

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Report RL30622

*ELECTRIC-DRIVE PROPULSION FOR U.S. NAVY
SHIPS: BACKGROUND AND ISSUES FOR CONGRESS*

Ronald O'Rourke, Foreign Affairs, Defense, and Trade Division

Updated July 31, 2000

Abstract. , The Navy in January 2000 selected electric-drive propulsion technology for use on its planned next-generation DD-21 land-attack destroyer and is considering it for use on other kinds of Navy ships as well. Electric drive poses issues for Congress concerning its costs, benefits and risks, and how the technology should be integrated into the DD-21 program or other ship-acquisition programs.

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Electric-Drive Propulsion for U.S. Navy Ships: Background and Issues for Congress

July 31, 2000

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Electric-Drive Propulsion for U.S. Navy Ships: Background and Issues for Congress

Summary

The Navy in January 2000 selected electric-drive propulsion technology for use on its planned next-generation DD-21 land-attack destroyer and is considering it for use on other kinds of Navy ships as well. Electric drive poses issues for Congress concerning its costs, benefits and risks, and how the technology should be integrated into the DD-21 program or other ship-acquisition programs.

Several foreign countries are developing or using electric drive in commercial or naval ships. The U.S. Navy's electric-drive development effort centers on the Integrated Power System (IPS) program. Several private-sector firms in the United States are now pursuing electric drive for the U.S. Navy market.

Electric drive offers significant anticipated benefits for U.S. Navy ships in terms of reducing ship life-cycle cost, increasing ship stealthiness, payload, survivability, and power available for non-propulsion uses, and taking advantage of a strong electrical-power technological and industrial base. Potential disadvantages include higher near-term costs, increased technical risk, increased system complexity, and less efficiency in full-power operations. The current scarcity of precise and systematic estimates of the costs and benefits of electric drive makes it difficult for policymakers to assess the relative cost-effectiveness of differing technical approaches to achieving electric drive. Some of the risks involved in developing electric-drive technology have been mitigated by the successful development of electric-drive technology for commercial ships; estimates of the amount of remaining risk vary.

The Navy has stated that developing common electric-drive components is feasible for several kinds of Navy ships and that pursuing electric drive technology in the form of a common family of components could have advantages for the Navy. The potential savings associated with a common system are difficult to estimate, but could be substantial. The concept of developing a common system or family of components poses issues for policymakers concerning the extent of commonality across electric-drive-equipped Navy ships and the use of competition in the development and procurement of electric-drive technology.

Much of the debate over electric drive concerns electric motors. The five basic types in question – synchronous motors, induction motors, permanent magnet motors, superconducting synchronous motors, and superconducting homopolar motors – differ in terms of their technological maturity, power-density, and potential applicability to different Navy ship types.

The Navy's decision to use electric drive on the DD-21 raises several potential issues concerning the acquisition strategy for the ship. Electric drive could be installed on Virginia (SSN-774) class submarines procured in FY2010, according to the Navy. Other candidates for electric drive include the Navy's planned TADC(X) auxiliary dry cargo ships, the Navy's planned joint command and control (JCC[X]) ships, the second through fifth LHA replacement ships, future aircraft carriers, and possibly the new cutters to be procured under the Coast Guard Deepwater project.

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Electric Drive Propulsion for U.S. Navy Ships: Background and Issues for Congress

Introduction and Key Findings

Introduction

This report provides background information and discusses issues for Congress regarding the use of electric-drive propulsion technology (as opposed to traditional mechanical-drive technology) on U.S. Navy ships. As a result of technological developments over the last few years, electric-drive technology has matured to the point where the Navy has selected it for use on its planned next-generation DD-21 land-attack destroyer and is considering it for use on other kinds of Navy ships as well.

Electric-drive technology would change the way that U.S. Navy ships transmit power from their engines to their propellers, as well as the way that they manage and distribute electrical power to both propulsion and non-propulsion systems. (Electric drive would not require the ship's engines to be changed; ships could continue to be powered by diesel engines, gas turbines, or steam turbines.) The Navy's decision to use electric-drive propulsion technology represents a technological shift for the Navy arguably comparable in significance to the Navy's shift from sail to steam power in the latter 1800s or the Navy's development of nuclear propulsion in the 1950s.

Electric-drive technology is being pursued by several foreign navies, most notably in Europe, and is being incorporated into numerous commercial ships, especially cruise ships. Electric-drive propulsion, particularly when installed as part of a ship-wide integrated electrical power system, could generate substantial capability and life-cycle cost benefits for U.S. Navy ships. Electric-drive technology, however, still requires development work, and integrating it into nearer-term U.S. Navy ship-acquisition programs, particularly the DD-21 program, involves a degree of technical risk.

The debate over whether, when, and how to incorporate electric-drive technology into Navy ship-acquisition programs has developed rapidly over the last three years. Key developments over this period include the following:

- In 1997, the Naval Studies Board of the National Research Council included a substantial discussion of electric-drive technology in a major 9-volume report on key technologies for the Navy and Marine Corps for the period 2000-2035.¹
- In 1998, U.S. firms involved in developing electric-drive technologies began to intensify their efforts and publicize them to both policymakers and the two shipyard-led industry teams that are competing for the right to design the DD-21 destroyer. These teams began to more intensively explore the potential for equipping the DD-21 with electric drive.
- In June 1998, the Senate Appropriations Committee directed the Secretary of the Navy to provide a report to the committee on the idea of a common electric-drive system for the DD-21 and later ships in the Virginia (SSN-774) class attack submarine program.
- In March 1999, the Navy delivered the report to Congress. The report stated that developing common electric-drive components is feasible for several kinds of Navy ships and that pursuing electric drive technology in the form of a common family of components could have advantages for the Navy.
- In May 1999, the Navy completed and began testing its full-scale, land-based electric-drive demonstration system in Philadelphia.
- In January 2000, the Navy announced that the DD-21 class would be equipped with electric drive and that proposed funding for development of electric-drive technology was being increased by about \$250 million over the period FY2001-FY2005.²

Electric-drive propulsion poses a number of issues for Congress concerning its potential costs, benefits and risks, and how the technology should be integrated into the DD-21 program or other ship-acquisition programs. Although Congress has approved funding for Navy research and development work on electric-drive in prior years, the Navy's plan to expand the scope of its electric-drive development effort and apply electric drive to at least one new class of Navy ships may require Congress in coming years to make significant decisions relating to the technology. The decisions

¹ National Research Council. Naval Studies Board. *Technology for the United States Navy and Marine Corps, 2000-2035, Becoming a 21st-Century Force*. Washington, National Academy Press, 1997. Volume 2 (Technology), p. 16, 233-281, and Volume 6 (Platforms), p. 19-22, 105-107.

² For coverage of the Navy's January 2000 announcement, see Walsh, Edward J. A Fundamental Change of Direction. *Sea Power*, March 2000: 24-25; Brown, David. Electric Plant to Power DD-21 Destroyer. *Navy Times*, January 17, 2000: 10; Seigle, Greg. USN Decision on Electric Drive Means More Delays. *Jane's Defence Weekly*, January 12, 2000: 3; Castelli, Christopher J. Navy To Make DD-21 First Electric Drive Surface Combatant. *Inside the Navy*, January 10, 2000: 2; Suro, Roberto. Navy Plans High-Powered New Destroyer. *Washington Post*, January 7, 2000: A3; Department of Defense News Release 007-00, January 6, 2000, entitled Integrated Power Systems, Electric Drive Selected for New Navy Destroyers.

that Congress reaches could have a profound affect on future Navy capabilities, Navy research and development funding requirements, and the U.S. marine propulsion technological and industrial base.

Congressional Request. This report is the result of a January 31, 1999 request to CRS from Senator Trent Lott for analysis and conclusions concerning electric drive. Senator Lott requested that the study examine the application of electric drive to civilian cruise ships, commercial cargo ships, surface combatants, submarines and aircraft carriers. The request stated that the report not be limited to U.S. developments.³

Sources of Information. In response to Senator Lott's request, CRS in March 1999 circulated a 5-page list of questions on electric drive to Navy offices, the Defense Advanced Research Projects Agency (DARPA), the National Academy of Sciences, U.S. shipbuilding firms, firms involved in the development of electric-drive technology, and other organizations. Recipients were invited to respond in writing to any or all of the questions, as appropriate, to supplement their written responses with in-person briefings if they so desired, and to distribute the list of questions to other potentially interested parties.

Written responses, some quite extensive, were received in March and April 1999 from the U.S. Navy, the United Kingdom's Royal Navy, numerous industry sources, and additional respondents. Respondents included most of the parties to whom the list of questions was originally sent by CRS, plus additional parties that received the list of questions indirectly. Several respondents supplemented their written responses with in-person briefings, some quite extensive. After reviewing these materials, CRS posed some specific follow-on questions to some of the respondents to help clarify or elaborate certain points; these inquiries resulted in some additional written responses and telephone conversations.

These written responses, in-person briefings, and telephone conversations constitute the primary sources of information for this report. These sources were supplemented with additional file materials that CRS has collected on the topic since the late 1980s, when CRS began to track developments relating to electric-drive propulsion for Navy ships.

Key Findings

The key findings of the report are presented below. They can be divided into two groups: findings relating to electric-drive technology in general, and findings relating to the potential application of electric drive to specific U.S. ship-acquisition programs.

³ Letter from Senator Trent Lott to Congressional Research Service, January 31, 1999.

Electric Drive in General.⁴

Current Status of Electric Drive. Several foreign countries, particularly in Europe, have developed, are developing, or are using electric-drive technology in commercial ships, naval ships, or both. Much of the development work is government-financed. The British Navy's electric-drive program is particularly significant. The electric-drive systems used today in cruise ships and other commercial ships are generally made overseas, primarily in Europe. The three primary European-based electric-drive suppliers are Alstom (previously known as Cegelec), Asea Brown Boveri (ABB), and Siemens.

Electric-drive technology is used on a few U.S. government ships and is being developed in the United States by both the U.S. Navy and private industry. The Navy's effort centers on the Integrated Power System (IPS) program, which was established in 1995. As mentioned above, the IPS program recently completed construction of a full-scale, land-based electric-drive demonstration system. Testing of this system, located in Philadelphia, began in May 1999. The Navy's prime contractor for this system is Lockheed Martin, but much of the actual equipment was provided by Alstom. Several other firms are also involved. The Navy is proposing a total of more than \$300 million for research and development on electric drive during the period FY2001-FY2005.

Several private-sector firms in the United States are now pursuing electric-drive technology for the U.S. Navy market. At least three private-sector entities are offering complete electric-drive systems to the Navy:

- **Alstom**, which has marine operations in Britain, France, Germany, and the United States (in Pittsburgh and Philadelphia). The company supplies electric-drive systems featuring synchronous motors and is also developing systems featuring induction and permanent magnet motors.
- an industry team led by **General Dynamics Corporation**, a leading designer and builder of U.S. Navy ships. This team is developing an electric-drive system featuring a permanent magnet motor.⁵
- an industry team led by **Newport News Shipbuilding (NNS)**, another leading designer and builder of U.S. Navy ships. This team is also developing an electric-drive system featuring a permanent magnet motor.

In addition to these three entities, other U.S. firms are also involved in developing electric-drive technologies or components. These include, among others:

⁴ A basic description of electric-drive (as opposed to mechanical-drive) technology can be found in the background section of this report.

⁵ As discussed in the background section of the report, five kinds of electric motors are discussed in connection with electric-drive technology for ships – synchronous motors, induction motors, permanent magnet motors, superconducting synchronous motors, and superconducting homopolar motors.

- **American Superconductor**, which is developing a superconducting synchronous motor, and
- **General Atomics**, which is developing a superconducting homopolar motor that was previously under development for many years by the U.S. Navy.

Anticipated Benefits and Disadvantages. Electric-drive technology offers significant anticipated benefits for U.S. Navy ships in terms of reducing ship life-cycle cost, increasing ship stealthiness, payload, survivability, and power available for non-propulsion uses, and taking advantage of a strong electrical-power technological and industrial base. Electric drive has potential disadvantages in terms of higher near-term costs, increased program risk, increased system complexity, and less efficiency in full-power operations.

Electric Drive as a Technology Area. Although electric drive is often discussed as a specific system that could be available in the near future for the DD-21 program, many elements of electric-drive technology have the potential to evolve and improve over time. This suggests that policymakers might consider addressing electric drive as not simply a proposal for a specific system that might require a few nearer-term acquisition decisions, but as a broader technology area that might require longer-term management and oversight and a series of research, development, and procurement decisions stretching over the course of several years. If conducting longer-term management and oversight of electric drive is considered appropriate, it might be assisted by developing an electric-drive technology development roadmap or master plan extending perhaps 10 to 25 years into the future.

Near-Term Costs. Pursuing electric-drive will incur higher near-term costs than a strategy that places continued emphasis on mechanical-drive technology. Developing electric-drive technology for warships would require hundreds of millions of dollars in research and development funding in coming years, particularly if the technology is developed for submarines as well as surface ships, and if development of more advanced electric-drive technologies is pursued. Several (but not all) sources for this report stated that electric-drive systems initially would be more expensive to procure than mechanical-drive systems. The cost premium for a commercial electric-drive system (which might be suitable for use in Navy auxiliary ships) could be less. These sources, however, agreed that the procurement cost of electric-drive systems would come down over time, and that the higher initial costs of electric-drive systems would be more than offset over the longer run by reduced ship life-cycle operating and support costs.

Measuring and Assessing Cost Effectiveness. Several sources agreed that the cost-effectiveness of electric drive should be examined not by focusing on the electric-drive system or any of its components in isolation, but rather by examining the effect that electric drive has on overall ship cost and capability. In an expanded version of this perspective, the cost-effectiveness of electric drive might also be measured in terms of its effect on total fleet costs and capabilities. Estimates of the costs and benefits of electric-drive technology should arguably include measures that examine not just shorter- but also longer-term (i.e., life-cycle or total ownership) costs and warfighting effects.

Although electric-drive technology offers numerous potential cost and warfighting benefits for Navy ships, relatively few precise estimates are available on the magnitude of these benefits. If not redressed, the scarcity of precise and systematic estimates will make it difficult for policymakers to assess with any precision the potential cost-effectiveness of electric-drive technology in general and (probably more significant) the relative cost-effectiveness of differing technical approaches to achieving electric drive.

The Navy's interest in electric-drive technology is consistent with the decisions of commercial ship operators (especially cruise ship operators) and other navies in recent years to move to electric-drive technology for their own ships. The strong interest in electric drive by other navies (particularly the British Navy) suggests that electric drive offers a variety of warfighting and life-cycle cost advantages for naval ships. The interest shown by other navies in electric drive, however, also demonstrates that there are multiple technical approaches to electric drive that should be assessed.

Technical Risk. Incorporating electric-drive technology into Navy ship-acquisition programs could add technical or schedule risk to those programs. The potential amount of risk varies, depending on the exact configuration of the system in question. More advanced approaches to electric drive present greater potential technical or schedule risk, but also promise greater potential cost effectiveness.

Electric-drive components presenting potential technical or schedule risk include motor drives, motors, generators, the electrical distribution system, advanced propeller/stern configurations, and overall system design and integration. Issues to be addressed include demonstrating at full scale technologies that to date have been demonstrated at partial scale, improving thermal performance, achieving desired levels of acoustic quieting and shock resistance, and designing overall system interfaces, controls, and module specifications.

Some of the risks involved in developing electric-drive technology have been mitigated by the successful development of electric-drive technology for commercial ships. Some industry sources argue that the amount of remaining risk involved in developing electric drive for Navy use is low to moderate. Other sources suggest that the degree of risk may be higher, particularly if the technology is developed on an aggressive schedule. Technical risk involved in developing electric drive might be mitigated through more intensified research and development.

Common System. The Navy stated in its March 1999 report to Congress that developing common electric-drive components is feasible for several kinds of Navy ships and that pursuing electric drive technology in the form of a common family of components could have advantages for the Navy. The Navy and the other military services have used commonality in numerous acquisition programs over the years, and Navy leaders are now placing increased emphasis on the concept.

Potential advantages of a common electric-drive system (or a family of common components) include nearer-term cost savings due to streamlining of research and development costs, both nearer- and longer-term savings due to greater efficiencies in procurement, and longer-term savings due to the streamlining of fleet training,

operation, and support efforts. Potential savings are difficult to estimate, but could be substantial.

The concept of developing a common system or family of components poses issues for policymakers concerning the extent of commonality across electric-drive-equipped Navy ships and the use of competition in the development and procurement of electric-drive technology. Past acquisition experience clearly suggests that designing a unique electric-drive system for each kind of ship would *not* result in the most cost-effective application of electric drive across the fleet. Past experience, however, does not prove conclusively that it would be achieved by an approach that would install a common system or family of components on every kind of ship that is scheduled to be powered by electric drive. Commonality is not an end in itself but rather would be a strategy for policymakers to consider in seeking the most cost-effective path to apply electric-drive technology across the fleet. Policymakers might wish to assess the relative merits of both a maximally common approach and more mixed approaches that combine elements of commonality with elements of ship-specific solutions.

Pursuing a common electric-drive system or family of components could in theory lead to the emergence of a dominant or monopoly supplier to the Navy of electric-drive technology, components, and systems. In light of this possibility, policymakers who place a high value on the use of competition in defense development and procurement might consider taking actions aimed at ensuring that any Navy acquisition strategy for electric drive makes maximum use of competition between competing industry approaches prior to selecting the approach that would form the basis for the common system. From this perspective, it may also be appropriate to aim at ensuring that nearer-term acquisition decisions preserve, as much as possible, a potential for employing competition in the eventual development and procurement of follow-on electric-drive technologies, components, and systems. One possible approach would be to require the common electric-drive system to be designed to a so-called open architecture. Another possible approach would be to provide continuing funding to firms other than those who supply the current electric-drive system to finance continued development of potential competing technologies or components.

Motors. Much of the debate since 1998 over the application of electric-drive technology to U.S. Navy ships concerns the type of electric motor that should be used. The issue is highly charged because specific motor types are associated with specific firms competing for a part of the Navy's prospective electric-drive program. The electric motors associated with electric-drive systems for large ships can be divided into five basic categories – synchronous motors, induction motors, permanent magnet motors, superconducting synchronous motors, and superconducting homopolar motors.

The synchronous motor can be considered the most mature technologically in application to large ships. There is a consensus among both naval and industry sources that the synchronous motor, if scaled up to the higher horsepower ratings needed to move surface combatants and submarines at high speeds (i.e., 30+ knots), would be too large and heavy to be suitable for use on these ships. The most likely apparent opportunity for incorporating electric-drive systems using synchronous

motors (presumably commercially available systems) into the Navy's electric-drive effort would be to install them in large Navy auxiliary ships.

The induction motor is generally considered the second-most mature motor type for application to large ships, after the synchronous motor. It is the type of motor used in the Navy's full-scale, land-based electric-drive demonstration system. Most of the sources consulted for this report argue (or do not contest) that it can be sufficiently power-dense to be suitable for use on U.S. Navy surface combatants. By the same token, however, most sources – including the U.S. Navy in its March 1999 report to Congress – also argue (or do not contest) that the induction motor is not sufficiently compact or quiet to be suitable for use on U.S. Navy submarines. Using an electric-drive system with an induction motor (rather than the currently less mature permanent magnet motor) might help mitigate the risk of integrating electric-drive technology into the DD-21 program, but would preclude achieving motor commonality across surface ships and submarines.

The permanent magnet motor can be made quieter and significantly more power-dense than the induction motor – enough so that it is consequently considered suitable for use on submarines as well as surface combatants. Sources generally agree that the permanent magnet motor can be used in a common electric drive system for Navy surface ships and submarines. The Navy's March 1999 report to Congress focuses on the permanent magnet motor as the motor available in the nearer term that would be suitable for a common electric-drive system.

The permanent magnet motor is less mature technologically than the induction motor, and consequently at this point may pose more development risk to incorporate into a nearer-term ship-acquisition program such as the DD-21 destroyer. Sources differ regarding the amount of technical risk involved in scaling up the permanent magnet motor to full size. Some argue that the basic technological issues in permanent magnet motors have been resolved, and that scaling up the technology will not pose any new issues; others demur, arguing that scaling up is never risk-free. The Navy's decision, announced in February 2000, to delay the procurement of the first DD-21 by one year (to FY2005) will, other things held equal, reduce the risk associated with equipping the first DD-21 with an electric-drive system using a permanent magnet motor.

The superconducting synchronous motor, if successfully developed, could be more power-dense and quieter than a permanent magnet motor. The superconducting synchronous motor is less mature technologically than the permanent magnet motor and was not discussed in the Navy's March 1999 report. Most sources argue (or do not contest) that it cannot be matured quickly enough to be installed at acceptable risk on the first DD-21. Advocates of the superconducting synchronous motor, while not necessarily disagreeing, argue that the technology for this kind of motor has progressed in recent years and that the time needed to mature the technology may be less than others estimate. The firm developing this motor says that, with adequate funding, it could be developed and completed by 2009, making it possible to have the motor enter service with the fleet in 2012.

*The superconducting homopolar motor,*⁶ if successfully developed, could similarly be more power-dense and quieter than a permanent magnet motor. The Navy worked on developing the homopolar motor for many years starting in the mid-1970s. The homopolar motor, like the superconducting synchronous motor, is less mature technologically than the permanent magnet motor and was given little emphasis in the Navy's March 1999 report. Advocates of this motor, like those of the superconducting synchronous motor, argue that the technology for this kind of motor has progressed in recent years and that the time needed to mature the technology may be less than others estimate. The firm now developing this type of motor says that, with adequate funding, it could be developed and completed in 5 or 6 years.

Other (Non-Motor) Components. There is considerable potential for evolution and improvement in the non-motor elements of electric-drive technology. This is potentially significant, because with the partial exception of the motor drive, there has been relatively little discussion of how these other components could or should evolve or be improved.

Application of Electric Drive to Specific Ship-Acquisition Programs.

DD-21 Land-Attack Destroyers. Given the possibility that the DD-21's system might become the basis for a common electric-drive system for the Navy, the economic stakes for firms competing to build the system are potentially very high. The Navy's acquisition strategy for the DD-21 program gives the two industry teams that are competing for the right to design the DD-21 wide latitude in selecting the type of electric-drive system the ship would use. This approach is consistent with Navy and Department of Defense acquisition reform efforts.

The potential for the DD-21's electric-drive system to become the basis of a common electric-drive system, together with the Navy's acquisition strategy for the program, raise several potential issues for Congress. These issues concern: the DD-21 program schedule and its effect on the technical risk in developing electric drive; the adequacy of DD-21 program funding for development of electric drive; the achievability of the DD-21 ship procurement cost goal; the potential for evolving the DD-21's electric drive system over time; the appropriateness of the latitude given to the two DD-21 industry teams in determining the ship's propulsion system; and how to reconcile the potentially conflicting goals of optimizing electric drive for DD-21 and optimizing it for application to multiple Navy ship types.

Given the competing motor technologies now being pursued, there are numerous potential strategies that can be pursued concerning the type of motor used in the DD-21 electric-drive system. Sources differed regarding the amount of technical risk associated with incorporating different versions of an electric-drive system into the first DD-21. The lowest-risk option would appear to be a system using an induction motor connected by a traditional horizontal shaft at the stern of the ship to a fixed-

⁶ The term homopolar (i.e., unipolar) refers to the fact that this motor uses direct current (rather than alternating current) electricity and does not require either a reversal of current or electrical commutation. As a result, the magnetic field and the electrical current in the armature of a homopolar motor are constant over time and space (i.e., unvarying).

pitch propeller. With some added risk, the lead ship's system could include a permanent magnet motor rather than an induction motor. Eventually, an advanced propeller/stern configuration such as a podded propeller⁷ could be developed for the DD-21.

On June 14, 2000, Ingalls Shipbuilding, the leader of one of the two industry teams competing for the DD-21, announced that it had selected the NNS-led electric drive industry team for the preliminary design of an electric drive propulsion system and will incorporate the NNS-led team's permanent magnet motor design into its initial system design proposal for the DD-21.

Virginia (SSN-774) Class Submarines. Electric-drive technology in some form could be installed on follow-on Virginia-class submarines. Navy officials testified in June 2000 that a nearer-term electric-drive system could be ready for a Virginia-class boat procured in FY2010. Some industry sources suggested that it could be ready for a boat procured in FY2007 if a decision were made in the near term to pursue the option and adequate development funding was provided.

Some industry sources have suggested, and the Navy did not disagree, that electric-drive technology for submarines, if pursued ambitiously, has the potential for altering the stern of a Virginia-class submarine in a way that could reduce the procurement cost of the submarine (currently \$1.9 billion to \$2.0 billion) by as much as \$100 million. Pursuing electric-drive technology for submarines this ambitiously, however, would be very expensive: It could easily require hundreds of millions of dollars, or even more than a billion dollars, in research and development funding beyond the funding that the Navy has already programmed for development of electric-drive technology.

TADC(X) Auxiliary Dry Cargo Ships. The Navy's planned TADC(X) class of auxiliary dry cargo ships, the first of which was procured in FY2000, is a near-term candidate for electric-drive propulsion. As a large, slower-speed, non-combat ship now in procurement that is somewhat similar to a commercial cargo ship, it might be feasible and cost-effective to equip the TADC(X) with a currently available European commercial electric-drive system similar to those now being used for cruise ships.

JCC(X) Joint Command and Control Ships. Electric drive might similarly be a candidate for the joint command and control (JCC[X]) ships that the Navy plans to begin procuring in FY2004. If these ships are built to commercial-ship standards, the JCC(X) might be a candidate for a commercial electric-drive system. The operational requirements of the JCC(X), however, might require a Navy-developed electric-drive system with better quieting and shock resistance.

LHA Replacement Ships. LHD-8 – a modified Wasp (LHD-1) class ship that will be the first LHA replacement ship – is to be equipped with a hybrid propulsion plant consisting of a low-power electric-drive system for low-speed operations and a mechanical-drive system for higher-speed operations. The Navy is now assessing

⁷ See figure 3 in the background section (page 18) for an illustration of a podded propeller.

whether the second through fifth LHA replacement ships should be additional (and further-modified) LHD-1 class ships or a new-design amphibious assault ship known as the LHX. The further-modified-LHD option might, and the LHX option more certainly could, include a full electric-drive system.

CVN(X) Aircraft Carrier. The Navy's March 1999 report to Congress on electric drive states that while electric drive is feasible for future aircraft carriers, mechanical drive would be more appropriate for CVN(X)-1, the first of the Navy's planned class of next-generation aircraft carriers, which is to be procured in FY2006. The Navy's conclusion contrasts with a 1997 Naval Research Advisory Committee (NRAC) report on the CVN(X) that strongly endorsed equipping the CVN(X) with electric-drive technology. Policymakers may review the Navy's 1999 conclusion periodically (e.g., with the procurement of each carrier) to determine whether it remains valid.

Coast Guard Deepwater Cutters. The 1998 Navy-Coast Guard national fleet concept, with its emphasis on commonality, raises the possibility of using electric-drive on the new cutters that are to be procured under the Coast Guard Deepwater project. Equipping these cutters with electric-drive could produce ship capability and life-cycle cost benefits for the Coast Guard similar to those that electric-drive technology is expected to produce for the Navy, and potentially improve economies of scale for both the Navy and Coast Guard in the production, operation, and life-cycle support of ship propulsion systems. Incorporating electric drive into the Deepwater program, however, would pose several significant issues in terms of feasibility, cost, and program disruption, particularly since the first cutter is to be procured in 2002 and competing Deepwater industry teams have already completed much of their design work for the ship.

Background

Basic Description of Electric Drive

Electric vs. Mechanical Drive. A ship's drive system is the equipment that transmits power from the ship's engines to its propellers. It is roughly analogous to the transmission and drive shaft in a car, which transmit power from the car's engine to its wheels.

Most of the world's larger civilian and military ships today use a mechanical-drive system. In very simplified form, with a mechanical-drive system, the higher-speed revolutions per minute (RPMs) produced by a ship's engine (also known as the prime mover) are transmitted by a rigid shaft to a set of gears, known as reduction gears, that convert (i.e., reduce) these higher-speed RPMs to the lower-speed RPMs that are more appropriate for a larger ship's propeller. A second rigid shaft then transmits these lower-speed RPMs from the reduction gears to the propeller. Ships with multiple propellers have multiple engines, reduction gears, and sets of shafts.

With an electric-drive system, in contrast, a generator converts the engine's higher-speed RPMs into electricity. This electricity is then transmitted by an electrical

cable toward the stern of the ship, to a device called a motor drive or motor controller, which modifies the voltage and frequency of the electricity as needed for the ship's electric motor to operate properly and at the desired speed. The electric motor then converts the electricity into lower-speed RPMs that turn the propeller. Ships with multiple propellers have multiple electric motors and motor drives.

Figure 1 depicts the basic arrangements of mechanical- and electric-drive systems.

Integrated Electric Drive (Integrated Power System). Ships with mechanical-drive systems actually have two sets of engines. One set is used for ship propulsion, as described above. A second and separate set, connected to electrical generators, is used to generate electricity for all of the electrically powered equipment on the ship. A U.S. Navy Arleigh Burke (DDG-51) class destroyer, for example, has a set of four large gas-powered turbine engines for propulsion, and a second set of three smaller gas turbines that produce electrical power for the ship.

In a ship with a mechanical-drive system, the power-producing capability of the ship's propulsion engines typically represents 75 percent to 85 percent of the ship's total power-producing capability. This power-producing capability is devoted exclusively to ship propulsion and is not available for non-propulsion uses, even when the ship is stationary or traveling at low speed.

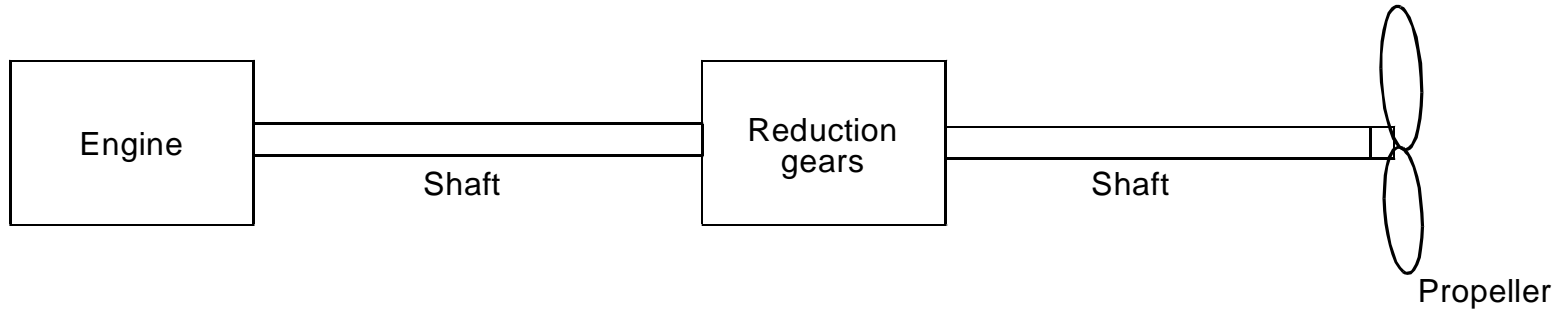
Ships with an electric-drive system, in contrast, can be designed so that a single set of engines produces a common pool of electricity that is used for both ship propulsion and the ship's non-propulsion electrical loads. Such a system is known as an integrated electric-drive (IED) system or integrated power system (IPS).

In ships with integrated electric drive, the electricity produced by the engines and generators is sent by cable to an electric switchboard that divides the electricity into two flows -- one for the ship's propulsion needs, and one for the ship's other electrical loads. The switchboard can alter the distribution of power between these two uses on a moment-to-moment basis, as needed, to meet the ship's propulsion and non-propulsion needs.

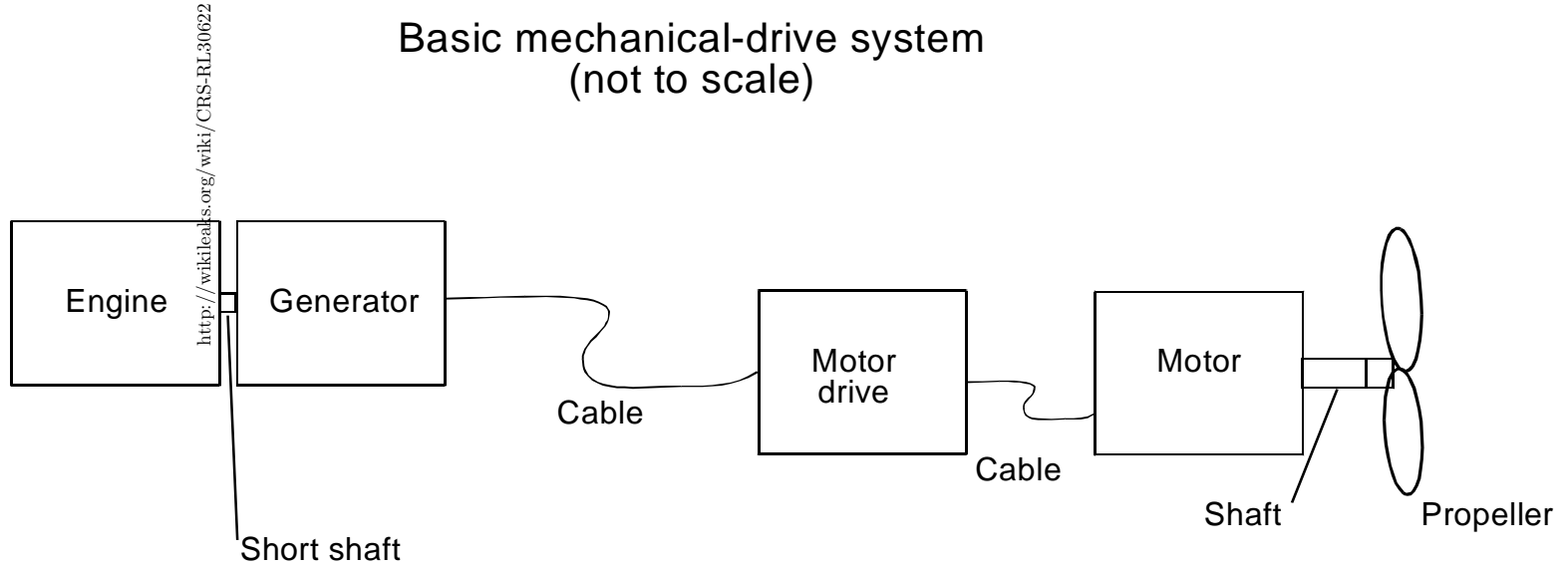
With an integrated electric drive, the large amount of power needed to propel the ship at high speeds is thus available, if needed, for other uses. Even when the ship is traveling at high speed, power can be momentarily diverted away from the propulsion system to a non-propulsion system that needs a short burst of high-strength power without appreciably slowing the ship down. An integrated electric drive is roughly analogous to the arrangement in the "Star Trek" science fiction television series, in which the captain of the star ship can order the ship's engineer to divert power from the ship's engines to its weapons or other systems.

All current proposals for using electric drive propulsion on U.S. Navy ships envisage an integrated electric drive system. *Consequently, in this report, the term electric drive is used to refer to integrated electric drive.* Figure 1 shows the basic arrangement of an integrated electric drive system.

Figure 1.



Basic mechanical-drive system
(not to scale)



Basic electric-drive system
(not to scale)

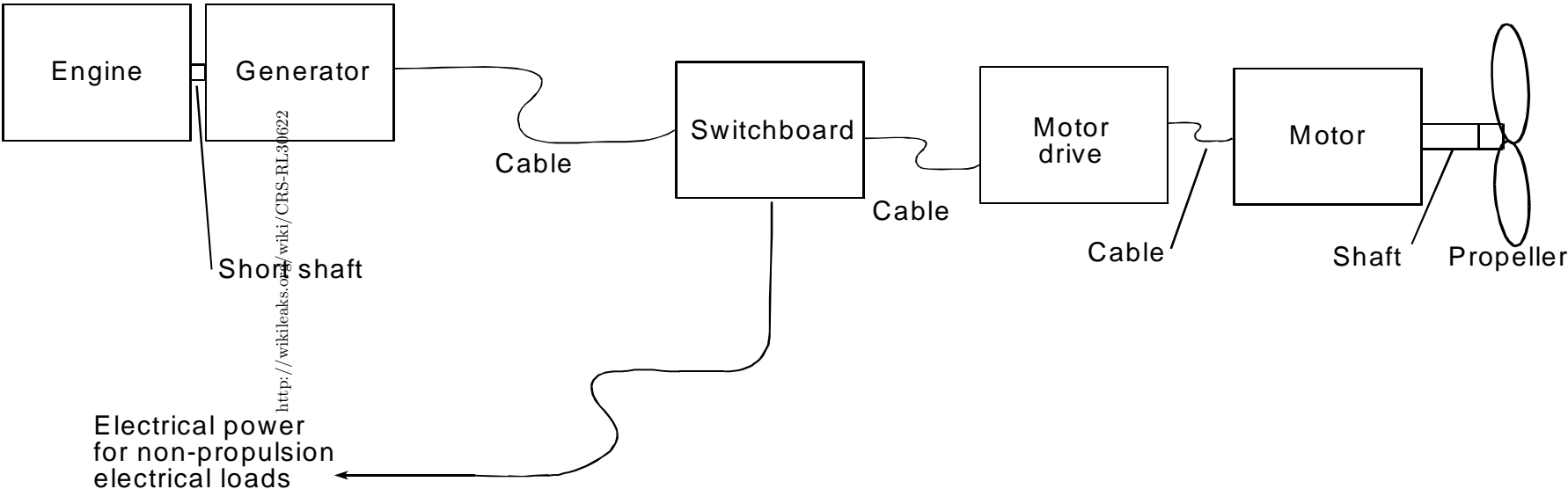
Key Components. As shown in Figure 2, an integrated electric drive system includes the following major elements:

- **Engines (also known as prime movers).** On U.S. Navy surface combatants, the engines are gas turbines (modified versions of jet engines used on commercial airliners) that burn jet fuel. On U.S. Navy submarines and most U.S. Navy aircraft carriers, the engines are steam turbines whose steam is created using heat produced by a nuclear reactor. On other ships (particularly those with lower maximum speeds), the prime movers can be diesel engines.
- **Generators,** which convert the mechanical energy produced by the engines – higher-speed RPMs – into electricity.
- **Electric switchboard,** which distributes the electricity to propulsion and non-propulsion needs.
- **Motor drives (also known as motor controllers),** which modify the voltage and frequency of the electricity as needed for the ship's electric propulsion motors to operate properly and at the desired speed.
- **Motors,** which convert electrical power from the motor drives to lower-speed RPMs suitable for a large ship's propellers.
- **Propellers,** which use the lower-speed RPMs to propel the ship through the water.
- **Non-propulsion power distribution system,** which distributes the remaining electrical power to the various non-propulsion electrical loads around the ship. This system includes additional cables, switches and power-conversion devices.

Common Electric Drive System. Over the last year or two, the terms "common electric drive" and "common integrated electric drive" have come into use to refer to an electric drive system that is designed with common components that can be installed on various types of Navy ships (e.g., submarines, surface combatants, amphibious ships, and auxiliary ships).

All-Electric Ship. On some ships today, some auxiliary systems are either steam-powered (e.g., space heaters, laundry equipment, and galley [kitchen] equipment), hydraulically (fluid) powered (e.g., steering systems and submarine diving systems), or pneumatically (air) powered (e.g., valve actuators and surface-ship turbine engine starters). On an integrated electric drive ship, converting these remaining non-electrical systems to electrical power would produce what is known as an all-electric ship. Some observers view the all-electric ship as a natural progression from an integrated electric drive ship.

Figure 2.



Basic integrated electric-drive system
(not to scale)

Motor Types. A key element in discussions of electric drive concerns the type of motor to be used. The motor types associated with electric-drive systems for large ships can be organized into the five general categories shown in the table below. They all convert electrical energy into mechanical energy (RPMs). They differ, however, in certain key characteristics, including the type of electrical current used – alternating current (AC) or direct current (DC) – the source of the magnetic field that is combined with the flow of electrical energy to create mechanical energy; and whether the motors conduct the electrical energy using conventional electrical wires or superconducting wires and associated technology.

Table 1. Basic Motor Types for Large-Ship Electric-Drive Systems

Long Name	Short Name
AC wound-field synchronous motor	Synchronous motor
AC induction (asynchronous) motor	Induction motor
AC permanent magnet synchronous motor	Permanent magnet motor
AC superconducting synchronous motor	Superconducting synchronous motor
DC superconducting homopolar motor	Homopolar motor

In addition, it should be noted that three versions of the **permanent magnet motor** have been discussed in connection with electric-drive systems for ships – the radial-gap (radial-flux) version, the axial-gap (axial-flux) version, and the transverse-flux version. These versions differ in the design and orientation of their fixed and rotating elements (their stators and rotors) and consequently in how electromagnetic lines of flux in the motors work to create mechanical movement. In short, a radial-gap motor can be described as a cylinder rotating within another cylinder; the axial-gap motor can be described as a disk spinning between two other disks, and the transverse-flux motor can be described as a rimmed disk whose rim spins inside slotted rings.

Anticipated Benefits and Potential Disadvantages

Anticipated Benefits.⁸ Electric-drive technology offers significant anticipated benefits for U.S. Navy ships in terms of reducing ship life-cycle cost, increasing ship stealthiness, payload, survivability, and power available for non-propulsion uses, and taking advantage of a strong electrical-power technological and industrial base.

Reduced Ship Life-Cycle Cost. Depending on the kind of ship in question and its operating profile (the amount of time that the ship spends traveling at various speeds), a Navy ship with an integrated electric-drive system may consume 10 percent

⁸ For examples of articles discussing the benefits of electric drive, see McCoy, Timothy J. Powering the 21st Century Fleet. *U.S. Naval Institute Proceedings*, May 2000: 54-58; Leonard, Robert E, and Thomas B. Dade. The All Electric Ship: Enabling Revolutionary Changes in Naval Warfare. *Submarine Review*, October 1998: 43-53.

to 25 percent less fuel than a similar ship with a mechanical-drive system. The Navy estimates a savings of 15 to 19 percent for a ship like a surface combatant.

In addition, electric drive makes possible the use of new propeller/stern configurations, such as a podded propulsor (see Figure 3), that can reduce ship fuel consumption further due to their improved hydrodynamic efficiency. Estimates of additional savings range from 4 percent to 15 percent, depending on the ship type and the exact propeller/stern configuration used.⁹

For fossil-fueled ships, fuel consumption is a major contributor to annual ship operating and support costs. Over the life of the ship, the savings from reduced fuel consumption promise to significantly outweigh the potential increase in initial procurement cost associated with electric drive, thus significantly reducing the ship's total life-cycle cost, also known as total ownership cost (TOC). The Navy is now placing increased emphasis on life-cycle cost in the acquisition process so as to more effectively capture the long-term cost consequences of its acquisition decisions.

In addition to savings on fuel, it is anticipated that electric-drive systems may require less maintenance and fewer crew members to operate than mechanical-drive systems. Electric-drive systems can be designed to be highly automated and self-monitoring. Reductions in maintenance and crew size would further reduce ship life-cycle cost.

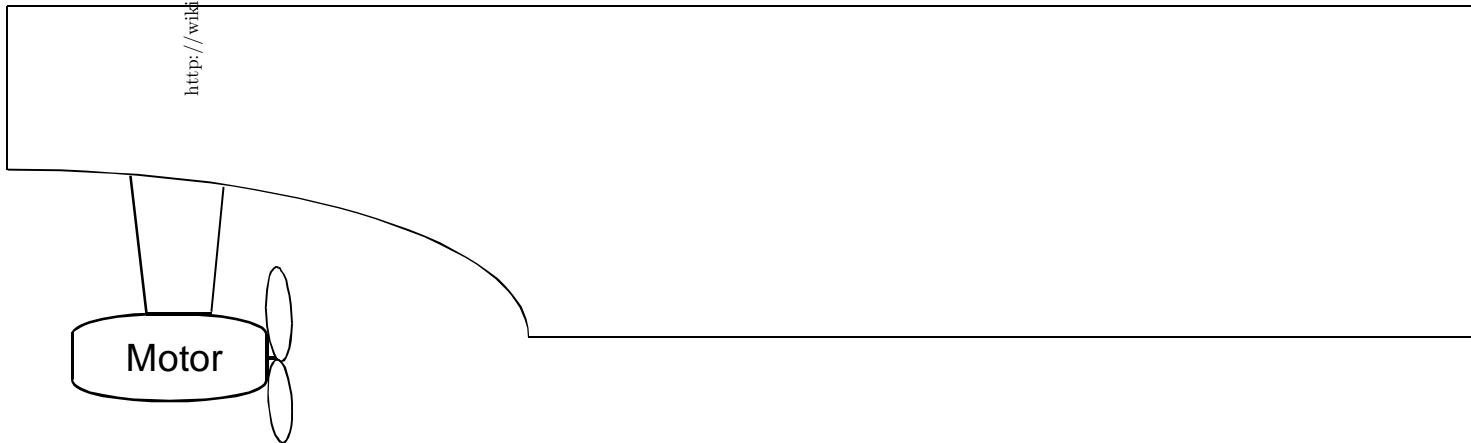
Increased Stealth. Electric drive promises to be significantly quieter acoustically than mechanical drive. Since acoustic noise is an important component of a ship's overall detectability, ships equipped with electric drive promise to be less detectible (i.e., more stealthy) than ships equipped with mechanical-drive technology.

⁹ A podded propulsor is a streamlined, roughly cylindrical pod with a propeller attached to one end (usually the front end) that is suspended from the bottom of the ship. The pod, which contains the electric motor driving the propeller, can be designed to swivel in a circle so as to direct the propeller's thrust in any direction and thereby steer the ship. A podded propulsor eliminates the need at the stern of the ship for a lengthy, exposed horizontal shaft leading to the propeller and a rudder for steering the ship. With a podded propulsor, there are fewer exposed components to create drag (i.e., resistance to forward movement), and the propeller encounters a more uniform (i.e., less disturbed) water flow, increasing its efficiency (i.e., its ability to use its RPMs to create thrust). Using podded propulsors can improve a ship's maneuverability by permitting a tighter turning radius and by giving it the ability to change the ship's direction of movement or its orientation even at very low speeds. A podded propulsor might also offer certain advantages in terms of maintenance and repair, since the pod can be detached and quickly repaired or replaced by a like unit without need for cutting an opening into the ship's hull and working around other equipment. For an article discussing podded propulsion systems, see Bonner, Kit. *Naval Propulsion for the 21st Century: The Azipod System*. *U.S. Naval Institute Proceedings*, August 1999: 74-76.

Figure 3.



Conventional propeller/stern arrangement with horizontal shaft, strut, propeller, and rudder
(not to scale)



Potential revised propeller/stern arrangement with rotating podded propulsor and no rudder
(not to scale)

<http://wikileaks.org/wiki/CRS-RL30422>

The significantly improved quieting promised by electric drive may be the single most important benefit of electric drive to the Navy's submarine community. Stealthiness is fundamental to a submarine's survivability and effectiveness and acoustic noise remains the most reliable method by which submarines can be detected and tracked at longer ranges. The Navy has expended significant resources over the last few decades on making its submarines increasingly quiet (so as to stay ahead of increasingly capable adversary submarine-detection equipment), and has stated that electric drive is needed to provide the next significant improvement in acoustic quieting on submarines.¹⁰

Although traditionally not as critical for surface warships, stealthiness – including acoustic quieting – is becoming increasingly important as a contributor to surface warship survivability and effectiveness. The improved acoustic quieting promised by electric drive thus promises to be of benefit to surface ships as well. In addition, electric-drive, by permitting a reduction in the volume devoted to air intakes and exhaust ducts, can reduce a surface ship's infrared signature and radar cross section. New propeller/stern configurations made possible by electric drive might reduce the wake signature of surface ships, which could reduce their detectability by remote overhead sensors and improve their chances of defeating much-feared wake-homing torpedoes.

Increased Payload. In a surface combatant, electric drive's reduced fuel consumption can translate into a reduction in the amount of space aboard ship required for fuel storage.¹¹ In addition, by eliminating the so-called "tyranny of the shaft line" -- the need, in a mechanical drive system, to install the engines, reduction gears, shafts, and propellers in a long line running along the bottom of the ship -- electric drive makes it possible to install the various parts of a surface combatant's drive system in positions that may use space aboard ship in a more efficient manner. For example, it may permit the ship's turbine engines to be located higher in the ship, reducing the amount of interior space required for the ducts that are needed to take air down into the engines and to carry exhaust gases away from the engine.

In both these ways, electric drive may free up space aboard the ship that can be used to carry additional payload (e.g., weapons or sensors). Freed-up space can also be used for other purposes, such as increasing the size of staterooms for members of the ship's crew so as to improve their quality of life aboard ship – an objective which has recently emerged as a Navy priority.

Increased Survivability. Electric-drive can improve ship survivability in several ways. Eliminating mechanical drive's tyranny of the shaft line can improve ship survivability by eliminating the possibility that one or more of the ship's long shaft lines will be thrown out of alignment and rendered useless by a nearby weapon explosion. Eliminating the requirement to locate elements of the ship's drive system

¹⁰ Bender, Bryan. US Navy Sets Sights on Electric Attack Submarine. *Jane's Defence Weekly*, July 26, 2000; Bowman, Frank L. "Skip." *Submarines in the New World Order. Undersea Warfare*, Spring 1999: 7.

¹¹ Alternatively, if fuel storage capacity is held constant, electric drive can permit an increase in ship operating endurance (range).

all in a straight line along the bottom of the ship makes it possible to place them in locations where they may be better protected from attack by certain weapons (e.g., mines).

Electric drive makes it possible to more widely distribute elements of the propulsion system around the ship, making it less likely that a single weapon might disable the entire drive system. With an integrated power system, the flow of power from distributed power sources can be rapidly reconfigured in the event of damage to the ship to ensure a continued supply of electricity to vital systems. Past experience with battle damage to naval ships suggests that this could be a very significant benefit. And for surface ships, electric drive permits smaller propulsion machinery spaces, which could facilitate damage control and permit greater use of automated damage-control technologies.

Increased Power Available for Non-Propulsion Systems. As mentioned earlier, electric drive makes large amounts of power available for non-propulsion uses such as powerful radars and sonars, laser weapons, high-power microwave weapons, electromagnetic rail guns, electrothermal guns, electromagnetic aircraft launch and recovery systems (i.e., electromagnetic catapults and arresting wires), or rapidly charging the batteries of unmanned air vehicles (UAVs), unmanned underwater vehicles (UUVs), and high-energy undersea sensor networks.¹² Some of these functions, particularly the weapons, may require peak power levels measured in tens of megawatts, and adding this much electrical-generating capacity to a mechanical-drive ship would incur substantial additional costs.¹³

Strong Technological and Industrial Base. Some elements of the Navy's current mechanical-drive systems, particularly reduction gears that have been specially engineered for quiet operations, are generally not found in commercial application, limiting economies of scale in their production and support. Advocates of electric drive argue that as commercial ships shift to greater reliance on electric drive, mechanical-drive technology will experience declining economies of scale that will not only increase its production and support costs, but also possibly reduce the incentive for manufacturers of mechanical-drive components to invest in further improvement of mechanical-drive technology. In contrast, advocates of electric drive argue, electric-drive propulsion will benefit from increasing production and support economies of scale, and will also be able to take advantage of rapid technological advances in the large and vibrant commercial electrical-power and electronics industries.

Potential Disadvantages. Electric drive has potential disadvantages in terms of higher near-term costs, increased program risk, increased system complexity, and less efficiency in full-power operations.

¹² See, for example, Bender, Bryan. US Navy Sets Sights on Electric Attack Submarine. *Jane's Defence Weekly*, July 26, 2000.

¹³ Electric drive in the future could also facilitate the replacement of today's prime movers (e.g., diesel engines, gas turbine engines, or steam turbines) and generators with more efficient power-producing technologies, including direct energy-conversion devices such as fuel cells.

Higher near-Term Costs. Pursuing electric-drive technology would incur higher near-term development costs than a strategy that places continued emphasis on mechanical-drive technology. Most sources also stated that electric-drive systems would initially be more expensive to procure than mechanical-drive systems.

Increased Program Risk. Sources for this report acknowledged that incorporating electric-drive (rather than mechanical-drive) technology into Navy ship-acquisition programs could add technical or schedule risk to those programs, since electric-drive technology is less mature than mechanical-drive technology for application to naval ships. Areas of potential technical risk in developing electric-drive technology, depending on the approach taken, include motor drives, motors, generators, the electrical distribution system, advanced propeller/stern configurations, and overall system design and integration.

Increased System Complexity. Electric drive can add complexity to the ship's design both in the number of major elements involved in the drive train¹⁴ and in the complexity of the ship's electrical system. Added complexity in general can raise potential concerns regarding issues such as overall system reliability and maintainability. Proponents of electric drive argue that the technology has shown itself to be highly reliable and maintainable after extensive use in cruise ships and other commercial ships.

Less Efficiency at Full Power. Electric-drive systems can be less efficient than mechanical-drive systems for full-power (i.e., maximum-speed) operations, due to the energy losses involved in converting RPMs into electricity, and electricity back into RPMs.¹⁵ Naval ships, however, typically spend only a small fraction of their time at full power. Typically, most of their time – about 80 percent, by one estimate – is spent at half-speed (roughly one-eighth power) or less. As a result, for naval ships, losses due to the somewhat lower efficiency when operating at full power will likely be more than offset by gains due to higher efficiency when operating at partial power.

Brief History of Electric Drive

Electric-drive technology dates to about 1910, following the development of the first large electric motors and generators. At that time, electric-drive systems (developed by the United States) and mechanical-drive systems employing reduction gears (developed by the British) were both being perfected and competed against one another. By the 1920s, the British developed a lightweight, high-efficiency mechanical-drive system, and mechanical drive emerged as the predominant ship propulsion technology. As summarized by one naval writer,

The history of electric propulsion in naval vessels began in 1912 with the US Navy's fleet collier Jupiter [AC-3], successfully powered by a Melville-McAlpine turbo-electric system and prototype for future capital ship installations. In 1919,

¹⁴ Some sources disagreed with this, saying that when auxiliary systems are taken into account, electric-drive systems can be made less complex than mechanical-drive systems.

¹⁵ This is why electric drive is viewed as not necessarily better than mechanical drive for commercial cargo ships that sprint between ports at consistently high speeds.

the US Congress, still refusing funds for aircraft carrier construction as such, made an allocation for the conversion of the Jupiter to the Navy's first, albeit experimental, aircraft carrier Langley (CV-1), which entered service in 1922.

Three 32,000 [shaft horsepower] New Mexico class turbine powered [mechanical drive] battleships were ordered in 1914 but, in build [during construction], it was decided to install a turbo-electric [i.e., electric-drive] system in the lead ship.... While this was a heavier [drive system] installation than those of the two sister ships, the New Mexico proved more economical, flexible, and provided better manoeuvrability. Nevertheless, during major refits over 1931-1933, all three ships were given new 40,000 shp [shaft horsepower] straight turbine [mechanical drive] installation[s] for an extra 0.75 kts [knots].

In 1915, two Tennessee class [battleships], similar to the New Mexico... were ordered. These were immediately followed by three almost identical [Colorado-class ships], also with turbo-electric propulsion. The foregoing five battleships were survivors of the 1922 Washington Naval Treaty under which 11 further projected electric-driven capital ships were cancelled....

Two further products of the treaty were the Lexington (CV-2) and Saratoga (CV-3), survivors of a class of six battle cruisers ordered over 1916-1919 and on which work was stopped on the slip. Work on the named ships restarted in 1922 to complete them as aircraft carriers, the U.S. Navy's first real two [ships] of the type.... During WWII, the US produced numbers of turbo-electric vessels due, to some extent, to a shortage of [reduction] gear-cutting capacity in those years.¹⁶

¹⁶ Wood, Geoffrey. *Electric Propulsion In Warships – Then and Now. Naval Forces*, No. 3, 1995: 20. Another naval analyst has written that:

a major U.S. Navy success story of the early part of [the 20th] century [was] turbo-electric drive for capital ships (five battleships and the battle cruisers completed as the carriers Lexington (CV-2) and Saratoga (CV-3)).... Turbo-electric power was abandoned only because the post-World War I naval arms treaties made it vital to save weight; geared turbines [used in mechanical-drive systems] were far lighter. The U.S. Navy was unique in adopting turbo-electric power for major warships (some [cruise] liners built after World War I also were turbo electric), probably because the pre-1914 United States had the world's most advanced electric power industry.

The U.S. Navy revived turbo-electric plants during World War II for destroyer escorts, because U.S. gear-cutting capacity was insufficient. As in capital ships, turbo-electric machinery carried a considerable cost in weight and volume. As it turned out, however, the necessary lengthening of the ships' hulls reduced hydrodynamic (wave-waking) resistance enough to balance off the extra weight, and the resulting Buckley (DE-51)- and Rudderow (DE-224)-class escorts were as fast as the geared turbine design would have been (which was not, in the event, built as planned). These ships apparently proved entirely satisfactory. (Friedman, Norman. *Navy Commits to Electric Drive. U.S. Naval Institute Proceedings*, April 2000: 4, 6.)

After World War II, mechanical-drive technology continued to be improved and remained the dominant approach. Among warships, electric-drive technology was widely adopted only for submarines, where the diesel-electric power plant became the standard system because it permitted the submarine to propel itself submerged for limited periods of time on battery power, without need for access to the atmosphere as a source of oxygen for use in burning a fossil fuel.¹⁷

In the years after World War II, electric-drive technology was occasionally reexamined for use on ships other than smaller diesel-electric submarines. The United States, for example, built two one-of-a-kind nuclear-powered attack submarines to experiment with the technology -- the Tullibee (SSN-597), which entered service in 1960 and was decommissioned in 1988, and the Glenard P. Lipscomb (SSN-685), which entered service in 1974 and was decommissioned in 1990. Electric drive was also used in some large commercial ships, such as the cruise ships Normandie (in 1936) and Canberra (in 1960).

These periodic experiments, however, tended to confirm that electric-drive technology, while promising, was not competitive with modern mechanical-drive technology for large submarines and surface ships. The Tullibee and Glenard P. Lipscomb, for example, were significantly slower than other Navy attack submarines due to limits on the power of their electric motors, and their drive systems were very maintenance-intensive.¹⁸

The post-World War II dominance of mechanical drive began to be challenged starting in the mid-1970s, when technological developments in motors and particularly motor drives made electric drive potentially more cost-effective than mechanical drive for larger naval ships.

With regard to motors, large warships require high-horsepower motors that are reliable, power-dense (i.e., compact), shock-resistant, and quiet, and that deliver their horsepower in the form of slow RPMs (suitable for slowly revolving ship propellers) but high torque.¹⁹ High-horsepower electric motors have existed for many years, but they tend to be high-RPM/low-torque machines rather than low-RPM/high-torque machines. In the 1980s, moderate-horsepower, low-RPM/high-torque electric motors were developed, but their horsepower was still not sufficient to move large warships

¹⁶(...continued)

Virginian-Pilot, February 11, 2000.

¹⁷ In a diesel-electric submarine, a diesel engine (using air drawn down from the surface through a snorkel) is used to generate electricity that is stored in batteries. This stored electrical power is then drawn from the batteries to power the ship during submerged operations.

¹⁸ See, for example, Lipscomb Exit May Have Lessons For Burke Electric Drive. *Navy News & Undersea Technology*, January 29, 1990: 2.

¹⁹ Torque is the twisting power of the motor on the shaft, measured in foot pounds of force. An everyday analogue can be found in doorknobs: a stiff or heavy doorknob requires the hand and arm to generate more torque to operate than does a light or loose doorknob. For motors, horsepower is the product of RPMs times torque, divided by 5252.

at high speeds. Only in the last several years has development work progressed on high-horsepower, low-RPM/high-torque electric motors that are sufficiently power-dense and quiet for use on surface combatants and submarines.

With regard to motor drives, only within the last few years has it been possible to develop devices that could handle the high amounts of electrical power associated with high-horsepower motors and convert it efficiently into the kind of high-quality (i.e., almost-distortion-free) power needed to ensure that an electric motor engineered to operate quietly will in fact operate quietly.²⁰ Developments in the last couple of years in power electronics – semiconductor-based electronic devices that are capable of handling large flows of power, as opposed to the much smaller flows of energy handled by the semiconductor chips in a computer – have progressed to the point where it is now possible to build high-capacity motor drives that can operate efficiently and deliver very-high-quality power to high-horsepower electric motors.

The development of semiconductor-based power-conversion devices also made integrated electric drive possible because these devices can efficiently convert large amounts of electrical power into differing forms needed for propulsion and non-propulsion uses. Electric-drive systems using AC motors²¹ control the speed of the motor by varying the frequency of the electric power fed from the motor drive. This made the electrical power unsuitable for other electrical systems on the ship, which require electric power at a stable frequency. As a result, older AC electric drive systems could be used only for ship propulsion and could not be integrated with other systems aboard the ship to produce an integrated electric drive.

In 1985, the United Kingdom took advantage of these developments and began building a new class of frigates, known as the Duke class or Type 23 ships, which employ a combined diesel-electric and gas turbine-mechanical drive propulsion plant. The ships use a lower-power diesel-electric drive system for quiet sonar-towing operations at speeds of up to about 15 knots, and a gas turbine-mechanical drive system for higher-speed operations up to the ships' maximum sustained speed of about 28 knots.²² The first Type 23 frigate entered service in 1990 and their drive systems have been favorably received. The ships use much less fuel than comparably sized mechanical-drive ships such as the U.S. Navy's Oliver Hazard Perry (FFG-7) class frigates, have demonstrated high reliability, and are very quiet compared to earlier ships when operating at lower speeds.

In 1987, the cruise ship Queen Elizabeth II underwent an overhaul during which its mechanical-drive system was replaced with an integrated electric-drive system.

²⁰ Distortions in the electrical power that is delivered to the motor can lead to noise-producing irregularities in the motor's performance.

²¹ Some electric motors are designed to use AC current; others are designed to use DC current. It was not practical to make conventional DC motors with ratings of more than about 10,000 or 15,000 horsepower. That was large enough to power small non-nuclear-powered submarines (where DC motors are widely used), but not enough to power large surface ships at higher speeds. Electric-drive-equipped surface ships thus tended to use AC motors.

²² For a discussion, see Preston, Christopher. Novel Electric Drive For the RN's Type 23 ASW Frigates. *Jane's Defence Weekly*, September 7, 1985: 473, 475, 477.

This system was also deemed successful in operation and set the stage for widespread adoption of electric-drive technology in the cruise ship industry. Today, most if not all cruise ships under construction in the world are being built with electric drive. Electric drive is now used almost exclusively in icebreakers and floating offshore oil platforms, and is becoming more common in passenger and car ferries. Other kinds of commercial ships now being built with electric drive include shuttle tankers, pipe-and cable-laying ships, and research ships.

Current Status of Electric Drive

Outside the United States. Several foreign countries, particularly in Europe, have developed, are developing, or are using electric-drive technology in commercial ships, naval ships, or both. Much of the development work is government-financed. These countries include the United Kingdom, France, Germany, Italy, the Netherlands, Finland, Sweden, Canada, Russia, Japan, South Korea, and China, among others.

Commercial Ships. The electric-drive systems used today in cruise ships and other commercial ships are generally made overseas, primarily in Europe. The three primary European-based electric-drive suppliers are Alstom (previously known as Cegelec)²³ and Asea Brown Boveri (ABB)²⁴ – which together account for most of the electric-drive systems in operation today – and Germany-based Siemens, which has a smaller market share but is considered a leader in permanent magnet motors and associated advanced motor drives.

Naval Ships. Developments regarding electric-drive technology in foreign (mostly European) navies include the following:

In General. Virtually all of the world's non-nuclear-powered submarines have electric-drive systems. Until recently, all of these submarines were diesel-electric boats that use diesel engines as the prime movers. A few countries, particularly in Europe, are now introducing so-called air-independent propulsion (AIP) systems that use fuel cells, Sterling engines, or closed-cycle diesel engines rather than conventional diesel engines as the prime movers. In spite of the change in the prime mover, however, these submarines are still electric-drive boats.²⁵

²³ As discussed later, Alstom is an international company headquartered in Paris that has marine operations in Britain, France, Germany, and the United States (in Pittsburgh and Philadelphia). The firm's marine business is directed from Britain.

²⁴ ABB's primary electric-drive facilities are in Finland and Italy.

²⁵ For examples of discussions of AIP systems on non-nuclear-powered submarines, see Walsh, Don. The AIP Alternative. *Sea Power*, December 1999: 34-37; Scott, Richard. Boosting the Staying Power of the Non-Nuclear Submarine. *Jane's International Defense Review*, No. 11, 1999: 41-44, 46, 48-50; Ritterhoff, Jurgen. Class 214 – A New Class of Air-Independent Submarines. *Naval Forces*, No. 5, 1998: 94-98, 100; Windolph, Wolfgang. The Better AIP. *Naval Forces*, No. 4, 1998: 114-116, 118-120; Scott, Richard. Power Surge. *Jane's Defence Weekly*, July 1, 1998: 24-27; de Lionis, Andres. The Allure of AIP Beckons the Navies of Developing States. *Jane's Intelligence Review*, February 1998: 39-41;

(continued...)

NATO. Electric-drive technology was endorsed as feasible and viable for future frigate-sized surface combatants by an October 1998 report from a NATO technical study group on future naval ship design.²⁶ This study was undertaken by 50 technical experts from more than 30 companies in 8 NATO countries (Canada, France, Germany, Italy, the Netherlands, Spain, Turkey, and the United Kingdom).

United Kingdom. In addition to the Type 23 frigates discussed above, whose electric-drive system was provided by Alstom (then Cegelec), the British Navy has two auxiliaries that use electric drive – a seabed operations vessel and a former commercial support ship that was converted into a forward repair ship. The United Kingdom is also using commercial (modified cruise ship) electric-drive systems in two new Albion-class amphibious ships and two new Wave-class auxiliary oilers, all now under construction, and on two planned logistics landing ships.

The British Navy has approved and recently re-endorsed a 1996 Marine Engineering Development Strategy that envisages using electric drive on future warships and auxiliaries. The British Navy is now seriously considering using electric drive on a variety of planned warship classes, including a medium-sized (by U.S. standards) aircraft carrier, a nuclear-powered attack submarine, and two surface combatants – the Type 45 destroyer and the Future Surface Combatant (FSC). The baseline design for the FSC includes electric drive. Given the now-established use of commercial electric-drive systems on recently ordered British amphibious and auxiliary ships, it appears likely that future classes of such ships in the British Navy will also use electric drive.

The British Ministry of Defence has funded development of advanced electric-drive technologies for possible use on future ships under an Integrated Full Electric Propulsion (IFEP) program established in 1996. These technologies include a transverse-flux permanent magnet motor being developed by Alstom and Rolls Royce. The British Navy plans to build a land-based IFEP technology demonstrator,²⁷ and is using electric drive on an experimental trimaran (three-hulled) research ship (the Triton) that is intended to explore hull and mechanical options for future warships.

²⁵(...continued)

Robertson, Thomas. Air Independent Propulsion. *Naval Forces*, No. 6, 1996: 36-39; Annati, Massimo. AIP Systems: a Solution for Everybody? *Military Technology*, No. 11, 1996: 107-108, 110-112; Donaldson, A. J. Submarine Power Sources For the Mission. *Naval Engineers Journal*, May 1996: 129-146 (includes comments by others).

²⁶ North Atlantic Treaty Organization. *NATO All Electric Ship, NIAG SG/54 Pre-Feasibility Study, Final Report*. NATO, Brussels, 1998. (Document AC/141-D/737, NIAG [NATO Industrial Advisory Group] - D(98) 9. For a published summary of this study, see Weigel, Dieter. NATO Study on An All Electric Warship. *Naval Forces*, No. 5, 1999: 45-49. The results of the NATO study are also briefly summarized in Pengelley, Rupert. Turning The Naval Propulsion Helm. *Jane's Navy International*, January/February 1999: 10-15.

²⁷ For a discussion, see Scott, Richard. Rivals [sic] Teams Power Up For Electric Ship Demonstrator. *Jane's Defense Weekly*, December 22, 1999: 12.

(As discussed below, the U.S. Navy is also participating in the Triton experimentation program.)²⁸

France. France's nuclear-powered submarines all use electric-drive technology. One press report states that "the French Navy is understood to have decided in principle to adopt integrated full electric propulsion for its future warships."²⁹ Jeumont Industrie in France is supplying an axial-gap permanent magnet motor for the new Scorpene-class non-nuclear-powered submarine being built in France for Chile and is currently developing a permanent magnet motor for use in the next French nuclear-powered submarine. According to one source, Jeumont is developing a type of electric motor not otherwise discussed in this report – a superconducting permanent magnet motor.³⁰

Germany. Germany is using electric-drive systems in minesweepers, an oceanographic ship (whose system incorporates a permanent magnet motor), and non-nuclear-powered submarines. The new Type 212 German non-nuclear-powered attack submarine, scheduled to enter service in 2003, will use an advanced submarine electric-drive system that includes fuel cells as an alternative to a diesel engine and a permanent magnet motor, both made by Siemens. A second German company, Magnet-Motor, is also involved in developing permanent magnet motors for use in all military services. Work on permanent magnet motors by both firms began in the 1980s. The German firm MTG (Marine Technische Gesellschaft) Marinetechnik reportedly has completed a design study for the German Ministry of Defense for a 3,000-ton SWATH (small waterplane area, twin-hull) electric-drive demonstration ship featuring a radial-gap permanent magnet motor; the ship is being built by the German shipbuilder Thyssen Nordseewerke and is expected to be completed in 2002.³¹

Italy. Italy is building its own German-designed Type 212 submarines; these ships will also use Siemens-made fuel cells and permanent magnet motors. ABB in Italy developed a prototype permanent magnet motor for the Italian submarine program, but the Italian Navy selected the Siemens motor.

Netherlands. A significant recent example reflecting state-of-the-art electric-drive technology in deployed form in a warship is the Dutch Navy's new amphibious ship Rotterdam, which entered service in 1998. This 12,750-ton ship has an electric-

²⁸ For more on the British Navy's electric-drive development efforts, see Pengelley, Rupert. Future Electric, Harnessing the Promise of IFEP. *Jane's Navy International*, July/August 1997: 14-15, 17-18, 20-21; Hodge, CG, and D.J. Mattick. The Electric Ship, an Update. *Review of Naval Engineering*, Vol. 51, No. 4: 11-18; and Pengelley, Rupert. Turning The Naval Propulsion Helm. *Jane's Navy International*, January/February 1999: 10-15. Electric-drive technology is also used on British-owned cruise ships.

²⁹ Pengelley, Rupert. Europeans Go For Electric Drive. *Jane's Navy International*, January/February 1999: 3.

³⁰ Electric drive is also being used in French cruise ships and chemical tankers.

³¹ Pengelley, Rupert. Europeans Go For Electric Drive. *Jane's Navy International*, January/February 1999: 3.

drive system provided by the firm Holec Ridderkerk featuring induction motors. The ship has a maximum sustained speed of 19 knots.³² In addition, “in January 1998 the Netherlands released its All Electric Ship (AES) strategy document, large parts of which are characterised as having been taken verbatim from the UK antecedent.”³³

Russia. Russia uses electric-drive technology in icebreakers. Given Russia’s history as a significant naval power and as a developer of various naval technologies (including both nuclear and gas-turbine propulsion), it is very possible that Russia may be attempting to develop (within available resources) more advanced electric-drive technologies.

In the United States. Electric-drive technology is used on a few U.S. government ships and is being developed in the United States by both the U.S. Navy and private industry.³⁴

U.S. Government Ships. U.S. government ships equipped with electric drive include the new U.S. Coast Guard icebreaker Healy, which was procured in FY1990-FY1993 and entered service in 1999, three older icebreakers, several Military Sealift Command (MSC)-operated TAGOS-type ocean surveillance ships procured between FY1979 and FY 1990, a few TAGS-type ocean surveying ships that were procured in FY1990-FY1996, and a few AGOR-type oceanographic research ships that are operated by academic institutions under the Navy’s University National Oceanographic Laboratory System (UNOLS).

U.S. Navy Study and Development Efforts. The Navy’s more recent electric-drive technology study and development efforts began in 1979 with an assessment of then-current technology in the area. Electric drive was selected by the Navy for use in the DDGX, which became the Arleigh Burke (DDG-51) class destroyer. This decision, however, was subsequently reversed due to concerns over cost and schedule risk.

In 1984, the Navy explored designs for a potential new frigate (FFX) intended to replace the Navy’s aging Knox (FF-1052) class frigates. The FFX program was subsequently cancelled but informed later Navy efforts on electric drive.

A series of Navy studies in 1986-1989 on a potential destroyer-like ship called the Battle Force Combatant included consideration of a variety of new propulsion technologies, including electric drive. This work was carried forward under the Integrated Warship Systems Demonstration Program (IWSDP), which was later dropped.

³² Electric-drive systems are also used in Dutch ferries.

³³ Pengelley, Rupert. Turning the Naval Propulsion Helm. *Jane’s Navy International*, January/February 1999: 10-15.

³⁴ For an overview of U.S. government and industry efforts on electric drive, see Walsh, Edward J. Transforming Shipboard Power. *Sea Power*, October 1999: 50-52.

In September 1988, then-U.S. Chief of Naval Operations Admiral Carlisle Trost endorsed the use of electric drive for the Navy's next surface combatant class.³⁵ In 1989-1993, the Navy funded full-scale advanced development work on an electric-drive system for a SWATH ship. In 1989, the Navy began development work on a zonal electrical distribution system (ZEDS), which would form part of an integrated electric-drive system. An AC version of such a system has been incorporated into later (Flight IIA) ships in the DDG-51 program. The first Flight IIA DDG-51 was procured in FY1994 and is scheduled to enter service in 2000. A DC version of ZEDS is under development.

U.S. Navy IPS Program. In 1992, a Navy program on a 21st Century Destroyer, using work done under the Navy's Advanced Surface Machinery Program (ASMP), concluded that incorporating an electric-drive system into the ship's design could actually reduce its procurement cost. To engineer this system and carry out risk-reduction work, the Navy in 1995 established its Integrated Power System (IPS) program.³⁶

³⁵ For information on this Navy interest in electric drive during this time, see, for example, Russell, James A. Navy Eyes Electric Drive For New Ships. *Navy News & Undersea Technology*, January 3, 1986: 1-2; Russell, James A. Electric-drive Ship Gets Boost From Superconductors. *Navy News & Undersea Technology*, July 3, 1987: 4; Elliott, Frank. Electric Drive Warships Will Revolutionize Ship Design. *Navy News & Undersea Technology*, June 6, 1998: 4-5 (see also related article on pages 1 and 3); Rumsey, Anne. Navy Ready To Award Work For Electric Drive. *Defense Week*, July 25, 1988; Black, Norman. Electricity Proposed As Power Of The Future For Navy Warships. *Hartford Courant*, September 30, 1988: 8; Trost Endorses Electric Drive, Promises Use In Future Ships. *Navy News & Undersea Technology*, October 3, 1988: 1, 3; Halloran, Richard. U.S. Plans Electric Power to Drive New Warships. *New York Times*, October 9, 1988: 37; Matthews, William. After 75 Years, Navy Returns to Electricity to Power Its Ships. *Defense News*, October 10, 1988: 6; Rumsey, Anne. Adm. Trost Puts Electric Drive Into High Gear. *Defense Week*, November 28, 1988: 5; Friedman, Norman. Electric Drive Revisited. *U.S. Naval Institute Proceedings*, December 1988: 149; Navy Begins Work on Propulsion System of the Future. *Navy News & Undersea Technology*, February 13, 1989: 4-5; Walsh, Edward J. Prime Movers. *Sea Power*, March 1989: 55-58; Rumsey, Anne. Navy Slows Drive For Electric-Powered Ships. *Defense Week*, May 15, 1989: 7; Lane, Maury. Navy Designs Radical Ship Propulsion System. *Defense News*, July 3, 1989: 1, 28; Superconductor Technology Would Cost 25% Less Than Navy Electric Drive Plan. *Inside the Navy*, August 28, 1989: 7; Electric Transmission and Podded Propulsors For the US Navy of the 2000s. *Maritime Defence*, November 1989: 355-356; Navy 'Integrated Electric Drive' R&D Accelerates. *Sea Power*, February 1990: 42-43; Navy Abandons Goal To Install Integrated Electric Drive on DDG-51 Destroyer. *Inside the Pentagon*, November 15, 1990: 3-4; Navy Officials Say Service Is Abandoning Electric Drive on DDG-512 Ship. *Inside the Navy*, November 19, 1990: 1, 11-12; Lawson, Richard. Advanced Ship-Propulsion Program Changes Name, Focuses on Affordability. *Inside the Navy*, November 18, 1991: 16; Rosenberg, Eric. It's Wait And See For Navy's Electric Drive. *Defense Week*, January 21, 1992: 2.

³⁶ For descriptions of the IPS program in its earlier stages, see IPS: The US Navy's Next-Generation Power/Propulsion System. *Maritime Defence*, December 1996: 278-279; Doerry, Norbert, et al. Powering the Future with the Integrated Power System. *Naval Engineers Journal*, May 1996: 267-282; Walsh, Edward J. Surface Fleet Looks To "All-

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In 1995, the IPS program supported advanced development work on a partial-scale axial-gap permanent magnet motor. This work was done by Newport News Shipbuilding, Kaman Electromagnetics Corporation (KEC) and the Naval Surface Warfare Center (NSWC) at Annapolis.

Since 1995, the IPS program has carried out full-scale advanced development work on electric drive. The IPS program recently completed construction of a full-scale, land-based demonstration electric-drive system. Testing of this system, located at the Naval Sea Systems Command (NAVSEA) Advanced Propulsion and Power Generation Test Site (APPGTS) in Philadelphia (on the site of the former Philadelphia naval shipyard), began in May 1999 and is scheduled to continue through FY2001.

The Navy is using this land-based system as part of a demonstration and risk-reduction effort for electric-drive technology in general and the DD-21 program in particular. A second goal is to develop the site as a test facility for future electric-drive technology developments. The Navy's prime contractor for this system is Lockheed Martin, but much of the actual equipment was provided by Alstom. Several other firms are also involved.

The IPS program is also testing electric-drive technology with the British Navy on the British technology demonstration ship Triton as part of a joint U.S.-U.K. technology demonstration effort. Specifically, the U.S. Navy will use the Triton to test elements of the IPS program's ship-wide power distribution system. At-sea tests with the Triton are scheduled to begin in 2001 and continue to 2003.³⁷

In 1998, the IPS program was transferred to the DD-21 program office. Although most of the Navy's work on electric drive in recent years has been carried out under the IPS program, additional work has been conducted outside the IPS program. For example, development work outside of the IPS program on electric drive for submarines was funded in FY1998. This work focused on developing submarine-suitable electric-drive systems that employ permanent magnet motors. Participants in this work include General Dynamics' Electric Boat and Electro-Dynamics divisions, Newport News Shipbuilding, KEC, Eaton, and Westinghouse Electro-Mechanical Division.

U.S. Navy Funding for Electric Drive. The tables below show prior-year (FY1989-FY2000) and programmed (FY2001-FY2005) Navy funding for electric drive.³⁸

³⁶(...continued)

Electric Ships." *Sea Power*, May 1996: 33-34.

³⁷ U.S. Department of the Navy. *TRIMARAN Integrated Power System (IPS) Project Plan*. Washington (?), 1998, 16 p. (December 1998)

³⁸ These tables do not include funding for research and development electric-drive technologies carried by the Office of Naval Research (ONR). Prior to FY1994, ONR funding for electric drive amounted to less than \$1 million per year. For FY1994 through FY2000, ONR funding for electric drive was as follows: \$4.3 million (FY1994), \$2.1 million (FY1995), \$13.1 million (FY1996), \$21.8 million (FY1997), \$21.5 million (FY1998), \$26.8

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Table 2. Prior-Year Funding for Navy Electric Drive Research and Development (FY1989-FY2000)
(millions of current dollars)

FY89	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97	FY98	FY99	FY00
24.0	29.0	52.0	12.4	9.1	9.7	13.7	28.7	21.3	26.5	31.8	25.7

Table 3. Programed Funding for Navy Electric Drive Research and Development (FY2000-FY2005)
(millions of current dollars)

FY00	FY01	FY02	FY03	FY04	FY05
25.7	84.1	106.3	69.3	26.9	10.0

Industry Development Efforts. Several private-sector firms in the United States are now pursuing electric-drive technology for the U.S. Navy market. At least three private-sector entities are offering complete electric-drive systems to the Navy:³⁹

- **Alstom (previously known as Cegelec)**, an international company headquartered in Paris that has marine operations in Britain, France, Germany, and the United States (in Pittsburgh and Philadelphia). The firm's marine business is directed from Britain. Alstom has been involved in marine electric-drive technology since 1920 and today is a leading international supplier of commercial and naval electric-drive systems. The company supplies electric-drive systems featuring synchronous motors and is also developing systems featuring induction and permanent magnet motors.⁴⁰

³⁸(...continued)

million (FY1999), and \$47.9 million (FY2000). Source: Department of Defense information paper on ONR initiatives supporting electric drive, provided to CRS by the Navy Office of Legislative Affairs, July 17, 2000 (LA-581-379).

³⁹ For discussions of industry efforts on electric drive, see Nagy, Barbara. *Propelled By Urgency*. *Hartford Courant*, April 14, 2000: E1; Lerman, David. *Power Play*. *Newport News Daily Press*, March 12, 2000: 1; Walsh, Edward J. *A Fundamental Change of Direction*. *Sea Power*, March 2000: 24-25; Schweizer, Roman. *Newport News-Kaman Unveil Electric Drive System to Challenge GD Team*. *Inside the Navy*, August 16, 1999: 5-6; Muradian, Vago. *NNS-Kaman Unveil Modular Electric Propulsion for DD-21*. *Defense Daily*, August 13, 1999: 6-8; Holzer, Robert. *Newport News Pushes Electric Drive Funding Scheme*. *Defense News*, May 31, 1999: 6; Holzer, Robert. *General Dynamics Pushes for Electric Drive*. *Defense News*, April 19, 1999: 4, 26.

⁴⁰ Alstom has supplied electric-drive components or systems for scores of commercial ships and several naval ships, including the British Navy's Type 23 frigates, which entered service starting in 1990, its two new Albion-class amphibious ships, which are scheduled to enter service in 2002-2003, and its two new Wave-class auxiliary oilers, which are scheduled to enter service in 2000-2001. In addition to being a principal supplier of the U.S. Navy's

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- an industry team led by **General Dynamics Corporation**, a leading designer and builder of U.S. Navy ships.⁴¹ The team includes, among other firms, GD's Electric Boat and Bath Iron Works shipyards, two other GD divisions, Westinghouse Electro-Mechanical Division (WEMD), Eaton Controls, and Northrop Grumman Marine Systems. This team is developing an electric-drive system featuring a permanent magnet motor.
- an industry team led by **Newport News Shipbuilding** (NNS), another leading designer and builder of U.S. Navy ships.⁴² The NNS-led team also includes, among other firms, Kaman Electromagnetics Corporation (KEC), which develops and builds electric motors and related systems. This team is also developing an electric-drive system featuring a permanent magnet motor.⁴³

In addition to these three entities, other U.S. firms are also involved in developing electric-drive technologies or components. These include, among others:

- **American Superconductor** of Westborough, MA, which is developing, in conjunction with **Rockwell Corporation**, a superconducting synchronous motor (and also superconducting wire and related technologies that could be incorporated into various electrical systems), and
- **General Atomics** of San Diego, CA, which is developing a superconducting homopolar motor that was previously under development for many years by the U.S. Navy.

Associated U.S. Navy Ship Programs

⁴⁰(...continued)

land-based electric-drive prototype system in Philadelphia, Alstom supplied the electric-drive systems for the U.S. Coast Guard's new icebreaker, the Healy, and the Navy's new ocean surveillance ship Impeccable (TAGOS-23), which was procured in FY1990 and entered service in 1999. For a discussion of Alstom's efforts in Philadelphia, see Holcomb, Henry J. Powering Up For Tomorrow's Ships. *Philadelphia Inquirer*, June 5, 2000.

⁴¹ General Dynamics owns 3 of the 6 shipyards that build major ships for the Navy – the Electric Boat Corporation of Groton, CT and Quonset Point, RI, which builds nuclear-powered submarines, Bath Iron Works Corporation of Bath, ME, which builds surface combatants and amphibious ships, and National Steel and Shipbuilding Company (NASSCO) of San Diego, CA, which builds auxiliary and sealift ships.

⁴² NNS, which is located in Newport News, VA, builds nuclear-powered aircraft carriers and nuclear-powered submarines for the Navy.

⁴³ Although the General Dynamics- and NNS-led teams are both developing electric-drive systems featuring permanent magnet motors, there are numerous differences in these two systems. For example, although both teams employ permanent magnet motors, the two teams have taken different approaches to the design of the control mechanisms for the motors, which is why the NNS-led team sometimes refers to its motor as a brushless DC motor.

Several U.S. Navy ship-acquisition programs are (or could be) associated with the Navy's electric drive program, including the following:

- **DD-21 Land-Attack Destroyer Program.** This is the Navy's program to develop and procure a next-generation surface combatant following the completion of the current Arleigh Burke (DDG-51) Aegis destroyer procurement program. The first DD-21 is to be procured in FY2005; a total procurement of about 32 ships is envisioned. As mentioned earlier, the Navy announced in January 2000 that the DD-21 will use electric drive. In light of this announcement, as well as the size of the DD-21 program and the fact that the DD-21 design is to form the basis of the Navy's next-generation CG-21 cruiser (which is to be procured following completion of the DD-21 program, perhaps sometime after FY2015), the DD-21 program is widely viewed as the ship-acquisition program currently most closely and significantly associated with the Navy's electric-drive effort.⁴⁴
- **Virginia (Ssn-774) Class Attack Submarine Program.** The first ship in this program, previously known as the New Attack Submarine (NSSN) program, was procured in FY1998. The second ship was procured in FY1999, and current plans call for the next five ships to be procured at a rate of one per year during the period FY2001-FY2005. A total of perhaps 30 ships might eventually be procured. The current Virginia-class design uses a mechanical-drive system, but there has been much discussion of building future units in the class to a modified design that uses electric drive. Because of the potential size of the program, and potential for the Virginia-class design to form the basis of the Navy's next-generation ballistic missile submarine (which might begin procurement around 2020), the Virginia class program is also significantly associated with the Navy's electric-drive effort.⁴⁵
- **TADC(X) Auxiliary Dry Cargo Ship Program.** This 12-ship program is intended to provide replacements for several older Navy auxiliary ships. The first TADC(X) was procured in FY2000. The second ship is to be procured in FY2001, and the remaining 10 ships in the program are to be procured during the period FY2002-FY2005.
- **JCC(X) Joint Command and Control Ships.** This program would replace the Navy's four aging command ships with a new class of four Joint Command and Control (JCC[X]) ships. Under the Navy's current plan, the first JCC(X) is to be procured in FY2004.
- **LHA Replacement Ship Program.** This program would replace the Navy's 5 aging Tarawa (LHA-1) class amphibious assault ships, which will reach the end of their 35-year service lives during the period 2011-2015. The first of

⁴⁴ For more on the DD-21 program, see CRS Report 97-700 F, *Navy DD-21 Land Attack Destroyer Program: Background Information and Issues for Congress*, by Ronald O'Rourke.

⁴⁵ For more on the Virginia-class program, see CRS Report RL30045, *Navy Attack Submarine Programs: Background and Issues for Congress*, by Ronald O'Rourke.

these ships, LHA-1, is to be replaced by LHD-8, which will be the eighth Wasp (LHD-1) class amphibious assault ship. LHD-8 is currently planned for procurement in FY2005, but its procurement could be accelerated to an earlier year. Ships to replace LHAs -2, -3, -4, and -5 will be procured after LHD-8.⁴⁶

- **CVN(X) Program.** The CVN(X) is the Navy's planned next-generation aircraft carrier. Under current Navy plans, the first ship in the program (CVN[X]-1) is to be procured in FY2006 and the second (CVN[X]-2) in FY2011.⁴⁷
- **Coast Guard Deepwater Project Cutter.** The Deepwater project is an ambitious Coast Guard program to replace its aging deepwater (i.e., far-from-shore)-capable cutters and aircraft. Under the Coast Guard's schedule for the Deepwater project, the first new cutter would be procured in FY2002.⁴⁸

Navy Report to Congress

The following is the executive summary of the Navy's March 1999 report to Congress on prospects for a common electric drive system for Navy ships, as reprinted on pages 9 and 10 of the April 12, 1999 issue of *Inside the Navy*.⁴⁹

The Navy evaluated electric drive alternatives for future submarines, surface combatants, and aircraft carriers. A team of Naval Sea Systems Command technical experts studied the feasibility of common electric components for integrated power (electric drive) systems on DD-21, CVN (X), and a VIRGINIA Class (NSSN) variant, and concluded the following:

- a common motor, or multiples of a common motor, could accommodate the range of main engine horsepower and shaft speeds for surface combatants, aircraft carriers, and submarines;
- generator commonality is limited to surface combatants and submarines due to size and power requirement incompatibility between these platforms and aircraft carriers; and
- a common motor controller for all applications is not practicable, however common subcomponents for all three applications is feasible.

⁴⁶ For more on LHD-8, see CRS Report RS20563, *Navy LHD-8 Amphibious Assault Ship: Background and Issues For Congress*, by Ronald O'Rourke.

⁴⁷ For more on the CVN(X) program, see CRS Report 98-359 F, *CVN-77 and CVX Aircraft Carrier Programs: Background and Issues for Congress*, by Ronald O'Rourke.

⁴⁸ For more on the Deepwater project, see CRS Report 98-830 F, *Coast Guard Integrated Deepwater System: Background and Issues for Congress*, by Ronald O'Rourke.

⁴⁹ For news coverage of Navy report, see Schweizer, Roman. Navy Wrestles With Prospects, Price of Electric Drive for Subs, Ships. *Inside the Navy*, April 12, 1999: 8-9; Holzer, Robert. U.S. Navy Strives To Electrify Future Combat Fleet. *Defense News*, April 5, 1999: 1, 50.

For future aircraft carriers, there will be a need for an increased electric generation capacity for loads such as an electric catapult and recovery system, future electrically powered weapons, and countermeasures. With this in mind, the Naval Sea Systems Command has studied options for electric drive and increased electric generation capacity. These studies concluded that while electric drive was feasible, mechanical drive is more appropriate at this time. For a ship the size of an aircraft carrier, electric drive did not offer space or weight savings over a steam driven mechanical drive design with appropriately sized turbine generators. In addition, the studies found that the most affordable method to achieve the objective of increased electric generating capacity was to use mechanical drive with larger turbine generators.

A Navy integrated power systems development program, which demonstrates a full size induction motor and other components for potential use in future surface ships, is entering the full-scale system test phase. This motor would not be appropriate for submarine use because it does not have the power density or acoustic performance needed for submarine applications.

The Navy has done extensive work to assess the viability of superconducting direct current (DC) homopolar motors for electric drive. However, there are significant technical challenges associated with homopolar motors. While some progress has been made in overcoming these challenges, more work is required. As a result, superconducting homopolar motors are not considered a viable option for electric drive at this time.

The Navy has concluded that the radial-gap permanent magnet motor possesses the power density, acoustic performance, and maturity of technology to be a viable propulsion motor common to the broadest range of ships. We believe that this is now possible due to the recent advancements in technology which are being pursued by industry in developing propulsion motors based on permanent magnet motor technology.

The Navy recognizes that a common development program would benefit both future surface combatants and submarines. Such a corporate program would allow the Navy to maximize life cycle cost reductions while satisfying performance needs of the broadest range of platforms. Common technology presents an opportunity for a common support structure such as personnel, training and maintenance facilities.

A Navy corporate integrated power system development program will benefit future ships, and allow horizontal integration of technology, components and training across the broadest range of ships. Therefore, the Navy is currently considering an expansion of its integrated power systems development to a corporate Navy program including state-of-the-art permanent magnet motor technology. Our plan includes an aggressive evaluation of the application of these technologies and the benefits associated for each type of platform including life cycle cost, logistics, and training reductions.

A summary comparison of mechanical drive versus an integrated power system (electric drive) is provided in Table I.

Table I - Mechanical vs. Integrated Power System Comparison

	Mechanical Drive	Integrated Power System with Induction Motor	Integrated Power System with Permanent Magnet Motor	Integrated Power System with Homopolar Motor
Submarine	<ul style="list-style-type: none"> - Does Not Meet Future Acoustic Needs 	<ul style="list-style-type: none"> - Does Not Meet Future Acoustic Goals - Required Induction Motor Size Is Too large 	<ul style="list-style-type: none"> + Meets Future Acoustic Goals + Meets Motor Size Requirements + Commonality Is possible 	<ul style="list-style-type: none"> - Significant Technology Development Required
Surface ship	<ul style="list-style-type: none"> - No Fuel Economy Improvement - No Flexible Power Distribution 	<ul style="list-style-type: none"> + Provides Flexible Power Distribution + Provides Naval Architectural Flexibility + Life Cycle Cost Savings + Lower Development Risk than Permanent Magnet Motor - Commonality Not Possible - Motor Larger than Permanent Magnet Motor 	<ul style="list-style-type: none"> + Commonality Is possible + Provides Flexible Power Distribution + Provides Naval Architectural Flexibility + Life Cycle Cost Savings 	<ul style="list-style-type: none"> - Significant Technology Development Required
Aircraft Carrier	<ul style="list-style-type: none"> + Future Power Generation Needs Can Be Met With New Electric Plant + Most Affordable Carrier Alternative 	<ul style="list-style-type: none"> + Potential to meet future goals - Not Cost effective for CVN (X) 	<ul style="list-style-type: none"> + Potential to meet future goals - Not Cost effective for CVN (X) 	<ul style="list-style-type: none"> - Significant Technology Development Required

Note that the table does not specifically address electric-drive systems featuring a regular (non-superconducting) synchronous motor (like those in the commercial electric-drive systems currently operating on cruise ships and other ships) or a superconducting synchronous motor.

Congressional Reaction to Navy Report

In marking up the Administration's proposed FY2000 defense budget, the House Armed Services Committee stated the following in reaction to the Navy's March 1999 report:

The committee notes the Navy's increased interest in the development of electric drive propulsion technology and the potential use of electric drive propulsion in future surface combatants and submarines, including insertion of an electric drive propulsion system in the DD-21 land attack destroyer and in the New Attack Submarine (NSSN) programs. A common integrated electric drive system appears to offer significant advantages, however, implementation of such a system has been limited by the technology needed for reliable electric motors of the power (approximately 30,000 to 50,000 shaft horsepower (shp)) required. The committee is aware that several alternative electric propulsion motor concepts have been proposed that are of varying degrees of technical maturity.

The statement of managers accompanying the conference report on H.R. 4103 (H.Rept. 105-746) directed the Secretary of the Navy to provide a report to the Congress which evaluates the installation of a common integrated electric drive system for DD-21, a NSSN variant, and [also evaluates designs for] the next-generation CV(X) aircraft carrier with both a common integrated electric drive system and a conventional mechanical drive system. The Secretary's report, dated March 1, 1999, states that the Navy has concluded that the radial-gap PM [permanent magnet] motor possesses the power density, acoustic performance, and maturity of technology to be a viable propulsion motor common to the broadest ranges of ships and that the Navy is currently considering expanding its IPS [Integrated Power Systems] development [program] to a corporate Navy program that will include state-of-the-art permanent magnet motor technology....

The committee will consider recommendations by the Secretary for further development and demonstration of electric drive propulsion technology for Navy ships which identify necessary funding and provide a program plan for development.⁵⁰

The Senate Armed Services Committee, in its markup, stated that the Navy's integrated power systems development effort

is designed to explore technologies required to develop power systems that could provide innovative means of generating, controlling, distributing, and using electricity in future ships. Propulsion motor development is a central focus of these explorations by the Navy and, independently, by commercial entities.

⁵⁰ H.Rept. 106-162 of May 24, 1999 (House Armed Services Committee Report on H.R. 1401, the FY2000 defense authorization bill), p. 194-195.

A recent Navy report entitled *A Report to Congress on Navy Common Integrated Electric Drive Systems*, addressed electric drive alternatives for future submarines, surface combatants, and aircraft carriers. The study reached several conclusions, to include: (1) the radial-gap permanent magnet motor has the power density, acoustic performance, and maturity of technology to be a viable propulsion motor common to the broadest range of ships; and (2) superconducting homopolar motors are not considered a viable solution for electric drive at this time. The committee believes that broad application is an important aspect of reducing life cycle costs to make the fleet of the future more affordable.

The committee understands that the Navy is considering an expansion of the integrated power system program to include permanent magnet motor technology. The committee encourages the Navy to take this step, however, the committee also expects the Navy to continue the technology base investment in superconducting alternatives as well, despite the fact that these technologies will not be mature enough for immediate applications such as DD-21.⁵¹

Issues for Congress

Electric-drive presents several potential issues for Congress that can be divided into two groups: those relating to electric-drive technology in general, and those relating to the potential application of electric drive to specific ship-acquisition programs. Each of these is discussed below.

Electric Drive in General

Electric Drive as a Technology Area. Although electric drive is often discussed as a specific system that could be available in the near future for the DD-21 program, many elements of electric-drive technology have the potential to evolve and improve over time. This suggests that policymakers might consider addressing electric drive as not simply a proposal for a specific system that might require a few nearer-term acquisition decisions, but as a broader technology area that might require longer-term management and oversight and a series of research, development, and procurement decisions stretching over the course of several years.

Given the many (and in some cases competing) possibilities for evolving and improving electric-drive technology over time, conducting longer-term management and oversight of electric drive as a technology area might be assisted by developing an electric-drive technology development roadmap or master plan extending perhaps 10 to 25 years into the future. Such a roadmap, updated periodically, could help place nearer-term investment decisions regarding electric-drive technology in the context of potential longer-term opportunities, risks, benefits, and implications. In recent years Congress has called for (and DoD has provided) master plans or roadmaps in other naval technology-development areas, such as mine warfare and anti-submarine warfare, that present multiple development opportunities stretching out over a period of several years.

⁵¹ S.Rept. 106-50 of May 17, 1999 (Senate Armed Services Committee Report on S. 1059, the FY2000 defense authorization bill), p. 232-233.

Near-Term Costs. As noted in the background section, pursuing electric-drive will incur higher near-term costs than a strategy that places continued emphasis on mechanical-drive technology.

With regard to development costs, mechanical-drive propulsion for naval ships is a very mature technology and would not necessarily require substantial amounts of additional research and development funding for future naval ships.⁵² Developing electric-drive technology for warships, in contrast, would require hundreds of millions of dollars in research and development funding in coming years, particularly if the technology is developed for submarines as well as surface ships, and if development of more advanced electric-drive technologies is pursued.

With regard to production costs, several (but not all) sources for this report stated that electric-drive systems initially would be more expensive to procure than mechanical-drive systems.⁵³ Although there are no precise figures, information provided by some sources suggest the procurement cost of a non-commercial (Navy-developed) electric-drive system might add a few tens of millions of dollars to the total procurement cost of a Navy combat ship. An additional cost of, for example, \$15 million to \$50 million would equate to an increase of about 2 percent to 6 percent in the procurement cost of a surface combatant costing about \$800 million (the approximate target cost in FY2001 dollars of a DD-21 class land-attack destroyer), or about 1 percent to 3 percent in the procurement cost of an attack submarine costing about \$2 billion (the approximate current cost of a Virginia [SSN-774] class submarine). The cost premium for a commercial electric-drive system (which, as discussed below, might be suitable for use in a Navy auxiliary ship) could be less than that of a Navy-developed system that is engineered to be more power-dense, quiet, and shock-resistant.

These sources, however, agreed that the procurement cost of electric-drive systems would come down over time if more systems are procured and production economies of scale for electric-drive technology increase, and as electric-drive technology continues to improve. They also agreed that the higher initial costs of electric-drive systems (both development and procurement) would be more than offset over the longer run by reduced ship life-cycle operating and support costs.

Measuring and Assessing Cost Effectiveness. Several sources agreed that the cost-effectiveness of electric drive should be examined not by focusing on the electric-drive system or any of its components in isolation, but rather by examining the effect that electric drive has on overall ship cost and capability. Focusing on the electric drive system or any of its components in isolation, they stated, could overlook certain effects of electric drive on total ship cost and capability and encourage optimization of the design at the system or subsystem level rather than the total-ship level.

⁵² An exception would be if a decision were made to attempt to achieve significant further improvement in the quieting of mechanical drive technology. Such an effort could require significant additional research and development funding.

⁵³ Some sources disagreed, stating that electric-drive would be roughly as expensive to procure as mechanical-drive technology, and perhaps (a couple of sources stated) somewhat less expensive.

In view of the potential for electric-drive technology to be applied across multiple ship types, and of the proposal for a common electric drive system (or common family of components), it might also be said that the cost-effectiveness of electric drive might best be measured not only in terms of its effect on the total costs and capabilities of individual ship designs, but also in terms of its effect on total fleet costs and capabilities. In this view, just as it would be inappropriate to optimize the application of electric drive at the system or subsystem level, so too it might be insufficient to assess the cost-effectiveness of electric drive at the level of individual ship designs. Such an approach may obscure the advantages of certain strategies for applying electric drive on a fleet-wide basis. In particular, it is possible that an electric-drive system that results in a suboptimal design for a particular kind of ship may nevertheless enable a more optimal application of electric drive across multiple ship types.

Since some of the most important projected potential benefits of electric drive technology, such as ship life-cycle fuel savings, would accrue over many years, any newly developed estimates of the costs and benefits of electric-drive technology should arguably include not just shorter-term issues such as initial research and development and procurement costs, but also measures that examine longer-term (i.e., life-cycle or total ownership) costs and warfighting effects as well.

Although electric-drive technology offers numerous potential cost and warfighting benefits for Navy ships, relatively few precise estimates are available on the magnitude of these benefits. Many of the available estimates, moreover, are single-point estimates that relate to the potential costs or benefits of a particular electric-drive technology concept as applied to a particular kind of ship under a specific set of assumptions regarding ship service life and typical ship operating speeds.

The scarcity of estimates that are both precise and systematic (rather than rough or single-point) is currently providing ample room for firms involved in developing electric-drive technology to make well-intentioned but also self-interested and sometimes-conflicting presentations to policymakers on the technology. If not redressed, the scarcity of precise and systematic estimates will make it difficult for policymakers to assess with any precision the potential cost-effectiveness of electric-drive technology in general and (probably more significant) the relative cost-effectiveness of differing technical approaches to achieving electric drive, incorporating it in the fleet, and improving it over time. As a result, policymakers would have more difficulty making decisions concerning electric drive, particularly decisions relating to longer-term development of the technology following an initial application to the fleet. More precise and systematic estimates may be produced by a study on electric drive that is being done for the Navy by the Rand Corporation and the Center for Naval Analyses.⁵⁴

The Navy's interest in electric-drive technology is consistent with the decisions of commercial ship operators (especially cruise ship operators) and other navies in

⁵⁴ Castelli, Christopher J. Navy Plans To Study Potential of Electric Drive for Ships and Subs. *Inside the Navy*, December 28, 1998:1, 10.

recent years to move to electric-drive technology for their own ships. The commercial ship industry's shift from mechanical- to electric-drive technology suggests that electric drive offers demonstrated advantages, at least for large ships, in areas such as reduced fuel costs, increased payload space (for cruise ship operators, this can translate into additional passenger cabins or other revenue-generating spaces), and perhaps reduced propulsion plant noise.

The strong interest in electric drive by other navies (particularly in Europe), and the reasons they have identified for pursuing the technology, provide support for the argument that electric drive offers a variety of warfighting and life-cycle cost advantages for naval ships. The British Navy's interest in electric drive is particularly noteworthy not only because of the variety of ships that the United Kingdom is considering to equip with electric drive, but also because the British Navy in the past has adopted (or invented) important naval technologies that were later adopted by the U.S. Navy.

The interest shown by other navies in electric drive, however, also demonstrates that there are multiple technical approaches that can be pursued. For example, both the 1998 NATO report and the British Navy's development program highlight the transverse-flux version of the permanent magnet motor as well as the radial gap (i.e., radial-flux) version, while permanent magnet motor efforts in the United States focus more exclusively on the radial-gap version. There are also actual or potential differences between the U.S. and European approaches to other components of electric drive, such as the ship-wide electrical power distribution system. Thus, while the interest shown by other navies in electric drive tends to support the U.S. Navy's interest in pursuing the technology, it also arguably underscores the need to carefully evaluate the relative merits of different technical approaches.

Technical Risk. As noted in the background section, incorporating electric-drive (rather than mechanical-drive) technology into Navy ship-acquisition programs could add technical or schedule risk to those programs, since electric-drive technology is less mature than mechanical-drive technology for application on naval ships. The potential amount of technical or schedule risk varies, depending on the exact configuration of the system in question. More advanced approaches to electric drive (e.g., those involving more advanced types of motors and motor drives) present greater potential technical or schedule risk, but also promise greater potential cost effectiveness.

In general, electric-drive components presenting potential technical or schedule risk include, among others,

- motor drives – which some sources identified as perhaps the foremost item of development risk,
- motors – whose development risk has been widely discussed,
- generators – if more advanced generator designs are pursued,
- the electrical distribution system,
- advanced propeller/stern configurations – if these are pursued, and
- overall system design and integration.

Issues to be addressed include:

- demonstrating at full scale technologies that to date have been demonstrated at partial scale,
- improving thermal performance (i.e., preventing the overheating of increasingly power-dense components),
- achieving desired levels of acoustic quieting and shock resistance, and
- designing overall system interfaces, controls, and module specifications, particularly for achieving system modularity and commonality and built-in potential for evolution and upgrades.

Some of the risks involved in developing electric-drive technology have been mitigated by the successful development of electric-drive technology for commercial ships. Some industry sources argued that the amount of remaining risk involved in developing electric drive for Navy use is low to moderate, and that development of electric drive poses less risk than has been posed by other technologies that the Navy has successfully developed. Other sources suggested that the degree of risk may be higher (moderate or even potentially high risk in some respects), particularly if the technology is developed on an aggressive (i.e., compressed) schedule.

The degree of technical risk involved in developing electric drive might be mitigated through more intensified research and development. Given the number of specific development possibilities that currently exist in electric-drive technology, the amount of research and development funding that until recently has been programmed for the area, and the potential cost and warfighting benefits of electric drive, an argument can be made that electric drive technology could be further elevated in priority as an element of the Navy's research and development account.

Electric drive, however, is by no means the only promising technology area for the Navy. If the Department of the Navy's overall budget (or its research and development budget) remains relatively stable, applying significantly more funding to research and development work on electric drive might come at the expense of other promising Navy technology programs. The potential implications for other Navy programs of providing increased funding might underscore the need for developing an electric-drive technology investment roadmap and more precise and systematic measures of the potential costs and benefits of electric drive technology.

Common System. As noted earlier, the Navy stated in its March 1999 report to Congress that developing common electric-drive components is feasible for several kinds of Navy ships and that pursuing electric drive technology in the form of a common family of components could have advantages for the Navy.

The Navy and the other military services have used the concept of commonality in numerous other equipment-acquisition programs over the years as a means of satisfying operational requirements in the most efficient manner possible. To cite just a few key examples, the Navy has long had common guns, missiles, weapon launchers, radars, sonars, computers, communication systems and other electronic systems that are installed across a variety of ship classes. In the area of ship propulsion, a single type of nuclear reactor (the S5W) was once used to power various Navy submarine classes, and a single type of gas turbine engine (the LM2500) has been used as the prime mover for every class of major surface combatant that the Navy has built since the 1970s. As the Navy has declined in size during the 1990s,

Navy leaders have placed even greater emphasis on achieving commonality of key equipment across ship classes as a means of preserving economies of scale in equipment development, procurement, and life-cycle operation and support.⁵⁵

Potential advantages of a common electric-drive system (or a family of common components) for application to both submarines and various surface ships include:

- nearer-term cost savings due to streamlining of research and development costs (i.e., avoidance of parallel development of differing electric-drive systems);
- both nearer- and longer-term savings due to greater efficiencies in procurement (i.e., achieving maximum economies of scale in the production process by producing larger numbers of a single system or family of components); and
- longer-term savings due to the streamlining of fleet training, operation and support efforts (i.e., maintaining common training, maintenance, and logistical support systems for all Navy ships equipped with the system).⁵⁶

The potential nearer-term savings are difficult to estimate due to the scarcity of precise and systematic cost estimates for researching and developing various potential technical approaches to electric drive. On the basis of preliminary cost information provided by sources for this report, however, it appears that the savings could easily total in the millions of dollars, and could, depending on the potential scope of avoided parallel development efforts, run into the tens or even hundreds of millions of dollars.

The potential long-term savings of pursuing a common system or family of components are similarly difficult to estimate due to both the relative scarcity of precise and systematic cost estimates for producing, operating, and supporting ships equipped with differing forms of electric drive, and uncertainty concerning how many classes of ships might be equipped with the technology, and when. Navy experience with other major acquisition programs, however, suggests that longer-term savings due to improved economies of scale in production and the streamlining of training, operation and support systems could be substantial.

The concept of developing a common system or family of components poses at least two potential policy issues for the Navy and Congress. One concerns the extent of commonality across electric-drive-equipped Navy ships; the other concerns the use of competition in the development and procurement of electric-drive technology.

⁵⁵ See, for example, Schweizer, Roman. Requirements Chiefs Approve Plan to Focus Common Technology Development. *Inside the Navy*, September 29, 1997, and Schweizer, Roman. Requirements Chiefs Consider Pooling Money to Develop Common Components. *Inside the Navy*, September 15, 1997.

⁵⁶ For an article discussing the potential benefits of a common electric-drive system, see Bartlett, E. L., Jr. Electric Propulsion: Commonality Is the Only Way. *U.S. Naval Institute Proceedings*, August 1998: 71-73.

Extent of Commonality. The concept of developing a common electric-drive system or family of components for all electric-drive-equipped Navy ships is sometimes posed, tacitly if not explicitly, as an alternative to developing a different electric drive system for each kind of Navy ship to be powered by electric drive. These two approaches, however, are simply two options at opposite ends of a spectrum of acquisition options that also includes mixed approaches that would combine elements of commonality with elements of ship-specific solutions. One example of a mixed approach would be to equip most types of ships with one kind of electric drive system while equipping one or more other types of ships with a different kind. Another example would be to install certain components as common elements across the fleet while permitting other components to vary more fundamentally by ship type. The Navy's March 1999 report appears to suggest that the second of these approaches may have merit.

Should agreement be achieved to broadly pursue electric drive, the goal for policymakers would be to optimize the cost-effectiveness of electric drive as it is applied across the fleet. Past acquisition experience clearly suggests that designing a unique electric-drive system for each kind of ship would *not* result in the most cost-effective application of electric drive across the fleet. Past experience, however, does not prove conclusively that it would be achieved by an approach that would install a common system or family of components on every kind of ship that is scheduled to be powered by electric drive.

Just as there are numerous kinds of equipment in the Navy that are installed in identical or near-identical form on various classes of ships, so too are there examples of equipment that differ significantly in design from one kind of ship to the next. Some cases of equipment differentiation across ship types are likely due to either a reduced emphasis in previous years on achieving the benefits of commonality or conscious decisions to continue operating non-conforming "legacy" systems on some ships because these systems would be expensive to replace. Other cases of equipment differentiation across ship types, however, might reflect a judgment that a maximally common approach was not the optimum solution on a fleet-wide basis. In the case of ship propulsion equipment, differentiation across the fleet in the past has resulted from differences across ship types in factors such as ship size, mission, or operational cycle.

From a public-policy perspective, commonality is not an end in itself but rather a strategy that policymakers would consider as they sought the most cost-effective path to apply electric-drive technology across the fleet. In seeking this path, policymakers might wish to assess the relative merits of both a maximally common approach and more mixed approaches. A technology-development roadmap or master plan and more precise and systematic estimates of the costs and benefits of various technical approaches to electric drive could keep the potential value of commonality in perspective and help policymakers identify the best overall path for the fleet.

Competition. If policymakers chose an acquisition strategy for electric drive featuring maximal or near-maximal commonality across ship types, a second potential issue to consider would be the role of competition in the development and procurement of electric-drive technology. Pursuing a common electric-drive system

or family of components could in theory lead to the emergence of a dominant or monopoly supplier to the Navy of electric-drive technology, components, and systems. Such a development could inhibit if not preclude the Navy from using competition in the development and procurement of follow-on electric-drive technology.

In light of this possibility, policymakers who place a high value on the use of competition in defense development and procurement – to secure benefits in restraining cost, improving product quality, encouraging adherence to scheduled delivery dates, and promoting innovation – might wish to consider measures aimed at ensuring that the Navy’s acquisition strategy for electric drive makes maximum use of competition among industry approaches prior to selecting an approach that would form the basis for the common system. They also might consider actions aimed at ensuring that nearer-term acquisition decisions, including the selection of a common system or family of components, preserve, as much as possible, a potential for employing competition in the eventual development and procurement of follow-on electric-drive technologies, components, and systems.

One possible approach for preserving a potential for competition in follow-on development and acquisition in electric drive would be to require the common electric drive system to be designed to a so-called open architecture – a set of nonproprietary and nonexclusive technical standards for key system characteristics that would permit firms other than those making the current system to compete on an equal footing with those making the current system for the development of follow-on technologies, components, or systems. This approach is now being used in other defense acquisition programs, particularly those involving electronic systems.

Another possible approach, not mutually exclusive with the previous one, would be to provide some amount of support to firms other than those who supply the current electric-drive system to finance continued development of potential competing technologies or components that are currently considered less mature or more risky than those used in the current common system. Providing such support would reduce the research and development savings associated with pursuing a common electric system or family of components, but would help bring to maturity alternative technical approaches that could be more cost effective than those that can be pursued today. Financially supporting potential downstream competitors and competing technologies could maintain a wider set of alternatives and some degree of competitive leverage for the federal government over the longer run as it sought to improve its electric-drive technology in step with technological advancements.

Motors. Much of the debate since 1998 over the application of electric-drive technology to U.S. Navy ships concerns the type of electric motor that should be used. Indeed, within the overall debate over electric-drive technology, perhaps no one issue has been more contentious. The issue is highly charged because specific motor types are associated with specific firms competing for a part of the Navy’s electric-drive program. A preference for a certain motor type can thus lead to a preference for the proposal of one firm or industry team over that of another.

As mentioned in the background section, the electric motors associated with electric-drive systems for large ships can be divided into five basic categories –

synchronous motors, induction motors, permanent magnet motors, superconducting synchronous motors, and superconducting homopolar motors. Each of these is discussed below.

Synchronous Motor. Of the basic motor types considered here, the synchronous motor can be considered the most mature technologically in application to large ships. It is the type currently used on most electric-drive-equipped commercial ships, particularly cruise ships, where it has been used successfully for more than a decade.

There is a consensus among both naval and industry sources that the synchronous motor, if scaled up to the higher horsepower ratings needed to move surface combatants and submarines at high speeds (i.e., 30+ knots), would be too large and heavy to be suitable for use on these ships. The synchronous motor, in other words, is considered insufficiently power-dense for application to these ships. Space and weight is a critical design consideration in the design of submarine propulsion plants. While space and weight considerations might be more relaxed in the design of a surface combatant's propulsion system, a high-horsepower synchronous motor is considered too large to fit into a podded propeller.

The synchronous motor can be made somewhat smaller and more power-dense through the application of water cooling (as opposed to air cooling). This approach, however, appears to be receiving no attention in industry efforts to develop electric-drive technology for the U.S. Navy, perhaps because the potential gain in power density is not deemed large enough to justify the effort.

The most likely apparent opportunity for incorporating electric-drive systems using synchronous motors into the Navy's electric-drive effort would be to install them in large Navy auxiliary ships. Compared to surface combatants and submarines, auxiliary ships are often designed for lower maximum speeds, their internal space constraints may not be as great, and their propulsion systems might not need to meet the same acoustic-quieting or shock-resistance standards. Consequently, it might be feasible to equip auxiliary ships with commercial electric-drive systems using moderate-horsepower synchronous motors that have already been developed for use on cruise ships.

Using a commercially available electric-drive system on an auxiliary Navy ship would raise an issue concerning the extent of commonality of electric-drive technology on U.S. Navy ships. Equipping auxiliary ships with commercial systems using synchronous motors would differentiate them from Navy ships using technology developed specifically for U.S. Navy use and thus reduce commonality in electric-drive technology within the U.S. fleet. It would also, however, make these auxiliary ships common in their electric-drive technology to cruise ships and other commercial ships, and permit them to take advantage of the economies of scale that exist for the production and life-cycle support for these systems, thus recouping at least some (and possibly much) of the cost-related benefits that commonality within the Navy would achieve. In addition, if future Navy auxiliary ships are built to more commercial (as opposed to U.S. Navy military) standards of construction, which is an option of growing interest to the Navy, it might be viewed as appropriate to equip these ships with commercial (as opposed to military) electric-drive technology.

Since today's commercially available electric drive systems are made by European firms, using a commercially available electric-drive system on an auxiliary ship could raise an issue regarding use of foreign-made propulsion technology on a U.S. Navy ship. Using a European-made commercial electric-drive system on a U.S. Navy ship might be viewed as acceptable in terms of contributing to a broader two-way U.S.-European trade in defense-related systems. Policymakers, however, have traditionally been highly resistant to the idea of relying on foreign-made technology in the construction of U.S. Navy ships (and many other major U.S. military platforms and weapons), in part on the grounds that it introduces a risk that unforeseen developments in a foreign country could delay or disrupt a U.S. shipbuilding program or complicate efforts to support these ships once they are in service, particularly in time of crisis or conflict.

Although U.S.-based firms involved in electric-drive technology development so far have chosen not to develop competing systems engineered to commercial performance specifications, commercial electric-drive systems in the future could still be built and supported in the United States, either by a U.S. subsidiary of a European firm or by a U.S. firm on license from a European firm. This could reduce any risk associated with using a European-developed commercial electric-drive system.

Induction Motor. The induction motor is generally considered the second-most mature motor type for application to large ships, after the synchronous motor.⁵⁷ As discussed earlier, it is the type of motor used in the Navy's land-based full-scale electric-drive demonstration system in Philadelphia.

The induction motor can be made significantly more power-dense than the synchronous motor. Most of the sources consulted for this report argue (or do not contest) that it can be sufficiently power-dense to be suitable for use on U.S. Navy surface combatants. By the same token, however, most sources – including the U.S. Navy in its March 1999 report to Congress – also argue (or do not contest) that the induction motor is not sufficiently power-dense or quiet to be suitable for use on U.S. Navy submarines.

Because the induction motor is generally considered more mature technologically at this point than the permanent magnet motor or superconducting motors, using an electric-drive system with an induction motor might help mitigate the risk of integrating electric-drive technology into the DD-21 program. Since the induction motor is not considered suitable for use on U.S. Navy submarines, however, using it on the DD-21 would preclude achieving motor commonality across surface ships and submarines in the Navy's electric-drive program.

In addressing the commonality issue, one potential issue for policymakers would be whether an electric-drive system for the DD-21 using an induction motor could be designed so that it preserved commonality with submarines in components other than the motor. Another would be whether the DD-21 system could be designed so that

⁵⁷ The induction motor discussed here is sometimes called the advanced induction motor to distinguish it from earlier, less sophisticated induction motors.

the induction motor could later be changed to a permanent magnet or superconducting motor.

Using the induction motor on the DD-21 or other ships would similarly raise a potential issue regarding use of foreign-developed technology, since this motor has been developed by a European-based firm (Alstom) while U.S. firms are focusing on developing permanent magnet and superconducting motors. As noted earlier, however, Alstom is the supplier of the induction motor (and other components) of the U.S. Navy's land-based electric-drive demonstration system and has established U.S.-based subsidiaries in Pittsburgh and Philadelphia to support its electric-drive efforts for the U.S. market.

Permanent Magnet Motor. The permanent magnet motor can be made quieter and significantly more power-dense than the induction motor – enough so that it is consequently considered suitable for use on submarines as well as surface combatants. As a consequence, the Navy and other sources generally agree that the permanent magnet motor can be used in a common electric drive system for Navy surface ships and submarines. As noted earlier, the Navy's March 1999 report to Congress focuses on the permanent magnet motor as the motor available in the nearer term that would be suitable for a common electric-drive system. Both the 1998 NATO report and the British Navy's current advanced electric-drive development effort similarly focus on the permanent magnet motor.

The permanent magnet motor is less mature technologically than the induction motor, and consequently at this point may pose more development risk to incorporate into a nearer-term ship-acquisition program such as the DD-21 destroyer. In contrast to the induction motor, a version of which is being tested in full-scale form at the Navy's land-based test site, the permanent magnet motor will be tested in quarter-scale (6,000-horsepower) form on LSV 2 (Large-Scale Vehicle 2), also known as the Cutthroat – the Navy's approximately one-quarter scale unmanned submarine for testing technologies for possible use on the Virginia-class submarine and other future submarines.⁵⁸ The Navy's decision to use a permanent magnet motor as the propulsion system for this important test vehicle reflects a certain amount of Navy confidence in permanent magnet motor technology, at least in quarter-scale form.

Sources differ regarding the amount of technical risk involved in scaling up the permanent magnet motor to full size. Firms involved in developing permanent magnet motor technology argue that the basic technological issues in permanent magnet motors have been resolved, and that scaling up the technology will not pose any new issues. Other sources, including firms involved in developing other types of motors, demur, arguing that scaling up is never risk-free.

A key issue at this point is whether the permanent magnet motor will be sufficiently mature for timely incorporation into the lead ship in the DD-21 class. The Navy's decision, announced in February 2000, to delay the procurement of the first DD-21 by one year (to FY2005) will, other things held equal, reduce the risk

⁵⁸ Costa, Keith J. Newport News, Electric Boat To Outfit Test Sub With Electric Drive. *Inside the Pentagon*, February 25, 1999: 15.

associated with equipping the first DD-21 with an electric-drive system using a permanent magnet motor. Under the previous plan to procure the first DD-21 in FY2004, most sources agreed that the time line for developing the permanent magnet motor for the lead ship would have been challenging. The additional year relaxes the situation somewhat, though much will still depend on the intensity of the development work that is conducted on the motor (which will depend in part on the amount of funding applied to the work), and on whether unforeseen issues arise in scaling up the technology.

If the permanent magnet motor is deemed not mature enough to install on the first DD-21, then policymakers could face the issue of whether the later ships in the DD-21 program should be built with the permanent magnet motor (when it matures), and whether earlier ships in the program built that are built with a different kind of motor (presumably an induction motor) should be backfitted with the permanent magnet motor at some point during their life. Addressing these issues could involve weighing the potential benefits of maintaining electric-drive component commonality within the DD-21 class against the potential benefits of commonality between the DD-21 class and other, subsequent, Navy ship classes that are equipped with electric drive.

U.S. (as well as European) firms are developing electric-drive systems using permanent magnet motor technology. The U.S. Navy can thus develop and procure an electric-drive system using permanent magnet motors without necessarily raising issues associated with use of foreign-made or foreign-developed technology.

As noted earlier, both the 1998 NATO report and the British Navy's development efforts focus to some degree on the transverse-flux version of the permanent magnet motor, as opposed to the radial-gap version being developed by U.S. firms. This raises a potential issue for Congress as to the relative risks and merits of the transverse-flux and radial-gap versions, and whether the U.S. development efforts should include more work on the transverse-flux version. Supporters of the transverse-flux version believe it to be the most efficient design, but some sources stated that it may pose greater development risks than the radial-gap design.

Some sources for this report, particularly supporters of other motor types, raised a particular technical issue regarding permanent magnet motors that they argued poses an elevated danger in the event of an internal fault (i.e., a short-circuit) in the stator windings – a problem that can occur in an electrical motor. The issue arises because it is not possible in a permanent magnet motor, as it is in other motor types, to turn off the motor's magnetic field.⁵⁹ This, they argued, creates the potential for a permanent motor to act as a generator in the event of an internal winding fault, particularly if the fault occurs as the ship is moving through the water at some speed.

⁵⁹ In a permanent magnet motor, the magnetic field that interacts with the electrical flow to create mechanical movement is created by permanent magnets that are built into the rotor. The magnetic field thus continues to exist when electrical power to the motor is cut off. On other motor types, the magnetic field is created as a product of electrical energy flowing through the motor, and ceases to exist when power to the motor is cut off.

This situation, they argued, would create a flow of electrical energy that would be fed by the motor back into the fault, exacerbating the damage caused by the fault.⁶⁰

Supporters of the permanent magnet motor stated that they are well aware of this issue. For most kinds of internal faults, they stated, it will not be necessary to turn off the magnetic field, because these faults can be managed through the design of the motor and motor controller. For one kind of fault (a turn-to-turn short), they stated, an ability to turn off the magnetic field could be useful, but the permanent magnet motor can cope with this fault by stopping or slowing its rotation through use of the same dynamic braking action as would be employed in the first stage of a “crashback” scenario.⁶¹ In sum, they argued that the issue of dealing with an internal fault, while real, can be addressed through careful system design and operation.

Some sources for this report also argued that the long-term stability of the material used for the permanent magnets is not proven in large-ship propulsion motors and could lead to reliability and maintenance issues over the life-cycle of the motor. Supporters of permanent magnet motors argued that permanent-magnet motors in industry use have proven themselves reliable over lengthy operating periods in other applications and that the careful motor design can make permanent magnet motors easier to maintain than existing electric motors.

Superconducting Synchronous Motor. The superconducting synchronous motor employs superconducting technology (including cryogenic equipment to cool the superconducting wire down to the temperatures at which the wires become superconducting) to achieve significantly stronger magnetic fields than non-superconducting motors. As a result, supporters of this motor type argue, the superconducting synchronous motor, if developed, can be more power-dense – and also quieter and more energy-efficient – than a permanent magnet motor.⁶² The U.S.

⁶⁰ Electrical motors, which convert electrical into mechanical energy, can also, if operated differently, act in the reverse manner – as generators that convert mechanical energy into electrical energy. The sources argued that in the event of a winding fault, even when electrical power to the motor could be cut off, the rotor would continue to spin for some time under its own momentum. As the rotor, with its permanent magnets, continued to spin past the stator, with its windings, an electrical current would be created that could flow back into the winding fault, causing additional heat and damage to the motor. This scenario, some sources argued, would be particularly relevant if the ship were moving at some speed, because the ship’s continued forward movement would cause the now-unpowered propeller to rotate as a result of the ship’s forward movement through the water. This rotation would be fed by the propeller shaft back into the motor, causing the rotor to spin even longer than it would simply as a result of its own momentum.

⁶¹ A crashback scenario is when the motor is commanded to go immediately from full ahead to full reverse. In accomplishing this, the system employs dynamic braking, in which electrical energy is drained from the motor so as to produce a reverse torque that helps bring the motor to a stop.

⁶² See, for example, Whitcomb, Clifford A. Commercial Superconducting Technology for Ship Propulsion. *The Submarine Review*, April 2000: 62-73; Kalsi, S., B. Gamble, and D. Bushko. *HTS Synchronous Motors For Navy Ship Propulsion*. Paper presented at Naval (continued...)

firm developing the superconducting synchronous motor – American Superconductor – is doing so as part of a broader effort to introduce high-temperature superconducting technology into the electrical power industry.

The superconducting synchronous motor is less mature technologically than the permanent magnet motor. Most sources argue (or do not contest) that it cannot be matured quickly enough to be installed at acceptable risk on the first DD-21. Advocates of the superconducting synchronous motor, while not necessarily disagreeing with the Navy about whether the technology would be ready for installation the first DD-21, argue that the technology for this kind of motor has progressed in recent years more than others might realize and that the time needed to mature the technology may be less than others estimate.

One technical issue regarding the superconducting synchronous motor concerned the cost, reliability, and survivability of its cryogenic systems. Supporters argue that this issue has effectively been resolved through the advent of high-temperature superconducting materials (as opposed to older, lower-temperature superconducting materials) and improved cryocoolers (refrigerator-like devices) that have made it possible to achieve the necessary amount of cooling without the need for using expensive liquid-helium cooling systems.

Some sources for this report raised a second issue – the possibility that the superconducting wire in these motors might degrade over long periods of motor use. In response, supporters of superconducting motors argue that superconducting wire has been extensively tested and that its durability is now being proven in the commercial electrical power industry.⁶³

The question is how quickly a superconducting synchronous motor might be made ready for use, how this would depend on the cost and intensity of the development effort that is undertaken, and how the technology might consequently fit into a longer-range strategy for incorporating electric-drive technology into Navy ships. The Navy has initiated a program to build and test a 1,000-horsepower proof-of-concept superconducting synchronous motor. According to American Superconductor, such a motor can be built and tested by 2004. Upon completion of this effort, the company says, a full-scale, 25,000-horsepower version could be developed and completed by 2009, making it possible to have the motor enter service with the fleet in 2012 – two years after the first DD-21 is scheduled to enter service, and about the time that the first follow-on DD-21s would enter service. American Superconductor says this estimated 10-year motor-development effort would cost a total of about \$90 million.

⁶²(...continued)

Symposium on Electric Machines, Annapolis, MD, October 26-29, 1998; Mulholland, Maxwell, and Stuart Karon. Letter to the editor, *U.S. Naval Institute Proceedings*, February 2000: 20, 22.

⁶³ For articles on the use of superconducting wire in the commercial electrical power industry, see Browne, Malcolm W. Power Line Makes Use of a Miracle of Physics. *New York Times*, November 3, 1998; and Spotts, Peter N. Electric Power Cables That Just Can't Resist. *Christian Science Monitor*, November 5, 1998.

Superconducting Homopolar Motor.⁶⁴ The homopolar motor, like the superconducting synchronous motor, uses superconducting technology to achieve stronger magnetic fields than non-superconducting motors. As a result, supporters argue, this motor can be made more power-dense, quieter, and energy-efficient than a permanent magnet motor. In addition, supporters argue, because the motor employs DC current, rather than the AC current used by all the other motor types discussed here, the homopolar motor permits the motor drive to be less complex and thus less expensive than the motor drives associated with the other motor types.⁶⁵

Because of its potential advantages, the Navy worked on developing the homopolar motor for many years starting in the mid-1970s. This effort has been continued in more recent years by General Atomics.

The homopolar motor, like the superconducting synchronous motor, is less mature technologically than the permanent magnet motor. In addition to the issue of the cryogenic system discussed above in connection with the superconducting synchronous motor, the homopolar motor poses a second development issue concerning the current collectors that transmit electrical power from the stationary parts of the motor to the rotating parts. Supporters of the homopolar motor state that solid-metal current collectors have been developed that are superior to the older liquid-metal current collector technology previously used in homopolar motors, and that this development risk has consequently already been substantially reduced. Others point out that these new solid-metal collectors have been tested only at smaller scales and need to proceed through larger-scale testing.

A third technical issue concerning homopolar motors concerns the need to transfer low-voltage, high-current electrical power – the kind used by homopolar motors – from the generator to the motor, and the implications that this would have for the design of the electric-drive system. Work on this issue is progressing, particularly in devising new designs for the motor that reduce the amount of low-voltage current needed to operate the motor, but these developments have not yet been tested at larger scales.

General Atomics believes that a quarter-scale (approximately 6,000-horsepower) homopolar motor can be built and demonstrated at sea in about two and one-half years at a cost of about \$15 million. This motor, supporters argue, could be tested on the quarter-scale LSV 2 submarine technology test vehicle. Designing, building and testing a full-scale (i.e., 40,000 horsepower) homopolar motor, the company says, would require additional time – perhaps another 2 or 3 years – and another \$100 million or so.

⁶⁴ The term homopolar (i.e., unipolar) refers to the fact that this motor uses direct current (rather than alternating current) electricity and does not require either a reversal of current or electrical commutation. As a result, the magnetic field and the electrical current in the armature of a homopolar motor are constant over time and space (i.e., unvarying).

⁶⁵ For a general discussion of the potential advantages of the homopolar motor and recent developments in homopolar motor technology, see Walters, J.D., et al. Reexamination of Superconductive Homopolar Motors for Propulsion. *Naval Engineers Journal*, January 1998: 107-116.

The Navy's March 1999 report to Congress on electric-drive technology, particularly its summary table, can be read to suggest that superconducting motors are of limited near-term relevance to the U.S. Navy's electric-drive technology program because of their less-mature status. Such an interpretation, which the authors of the report may not have intended, may be too dismissive of superconducting motor technology. Although superconducting motor technology appears likely to take longer to mature than permanent magnet technology, it might, if pursued, prove suitable for use in a common electric-drive system for use on Navy surface ships and submarines. The potential advantages of superconducting motors, combined with their least-mature status among the motor technologies discussed here, raises the issue discussed earlier of electric-drive technology posing longer- as well as shorter-term issues for policymakers, and of the potential need for a technology development roadmap stretching several years into the future.

Two Additional Comments. In discussing the issue of motor types, several sources offered two points that put the motor issue into additional perspective. First, they stated that the debate on motor types has led many discussions of electric-drive technology for the U.S. Navy to become excessively focused on the merits of competing motor designs as opposed to the more fundamental issue of the relative merits of mechanical- vs. electric-drive technology.

Second, they argued that an excessive focus on the merits of various motor types can obscure the issue that the motor is simply one component of an electric-drive system that contains several other major components as well. A motor that might seem the best when viewed in isolation might not lead to the best overall electric-drive system because of its effects on other elements of the system design. The goal, they point out, is to identify the best overall electric-drive system, not simply the best motor.

Other (Non-Motor) Components. Information provided by sources to this report indicates that there is considerable potential for evolution and improvement in the non-motor elements of electric-drive technology. This is potentially significant, because with the partial exception of the motor drive, there has been relatively little discussion of how these other components could or should evolve or be improved.

Some sources suggested, for example, that developing newer and more compact (i.e., lightweight) generators would reduce total system weight and space requirements and make it easier to locate a surface ship's gas turbine engines and generators higher in the ship, thus reducing the amount of internal ship volume occupied by the gas turbines' large air intakes and exhaust ducts – one of the potential architectural advantages of electric drive.⁶⁶

Similarly, there may be potential for developing motor controllers even more compact than the pulse-width modulated controllers now being developed. The ship-wide power electrical distribution system can evolve and change in terms of key

⁶⁶ For a discussion of advanced (permanent-magnet) generators for submarines, see Hollung, Achim. PM Generators for Submarines. *Naval Forces*, Special Issue No. 2, 1999 (Conference Proceedings, Subcon '99, German Submarine Technology): 40-43.

characteristics such as the type of current (AC or DC) and the voltage or voltages employed. And as mentioned earlier, electric drive makes it possible to evolve the propeller/stern configuration from the traditional arrangement (a horizontal shaft with a propeller at the end) to a more advanced arrangement.

The potential to evolve and improve the other components of an electric-drive system poses potential issues for Congress, including the following:

- How do these other components affect the overall cost-effectiveness of an electric-drive system?
- Have sufficient attention and resources been directed to the development of these other components?
- How should the potential for evolving these other components be factored into the design of the baseline electric-drive system for the DD-21?

Application of Electric Drive to Specific Ship-Acquisition Programs

DD-21 Land-Attack Destroyers.⁶⁷ Given the Navy's January 2000 announcement that DD-21 class ships will be equipped with an electric-drive system, a key follow-on issue for the program – and for the Navy's overall electric-drive effort – is what kind of electric-drive system the ship should employ. This issue is highly significant, because the choice of system type would likely amount to a decision as to which firms would be involved in building the system. Given the possibility that the DD-21's system might become the basis for a common electric-drive system for the Navy, the economic stakes for competing firms are potentially very high.⁶⁸

The Navy's acquisition strategy for the DD-21 program gives the two industry teams that are competing for the right to design the DD-21⁶⁹ wide latitude in determining the features of their proposed DD-21 designs, including the type of electric-drive system they will use. This approach is consistent with Navy and Department of Defense acquisition reform efforts.

The potential for the DD-21's electric-drive system to become the basis of a common electric-drive system, together with the Navy's acquisition strategy for the program, raises several potential issues for Congress, including the following:

⁶⁷ For an earlier discussion of the application of electric drive and related technologies to the design of a next-generation surface combatant with a full-load displacement of about 6,000 tons, see Levedahl, William J. A Capable, Affordable 21st Century Destroyer. *Naval Engineers Journal*, May 1993: 213-223.

⁶⁸ For a discussion, see Costa, Keith J. Work on DD-21 Might Give Electric Boat An Edge In Electric Drive Effort. *Inside the Navy*, August 13, 1998: 1, 4-6.

⁶⁹ These are the Blue team, which is led by General Dynamics' Bath Iron Works division and also includes, among other firms, Lockheed Martin as the combat system integrator, and the Gold Team, which is led by Litton Industries' Ingalls Shipbuilding and includes, among other firms, Raytheon as the combat system integrator.

- **Procurement Schedule and Risk.** Does the Navy's new plan for procuring the first DD-21 in FY2005 provide more than enough, not enough, or about the right amount of time for developing an electric-drive system for the first DD-21? How does the schedule for procuring the first ship affect the risk associated with incorporating electric drive into the ship, or the potential cost-effectiveness of the system that is developed?
- **Funding for Development.** Has the Navy provided adequate funding in its overall DD-21 development program for development of the ship's electric-drive system? How is the amount of risk associated with developing electric-drive technology affected by the amount of development funding?
- **DD-21 Procurement Cost Goal.** Is the Navy's unit procurement cost goal for the DD-21 – \$750 million in FY1996 dollars for the fifth ship built at each of the two shipyards that will build the ship – compatible with the objective of equipping the DD-21 with an electric-drive system? If equipping the DD-21 with the most cost-effective electric-drive system would result in a ship design that would cost more than \$750 million in FY1996 dollars, should this situation be resolved by increasing the \$750 million procurement cost goal, by reducing the procurement cost of the ship's propulsion system, or by reducing the procurement cost of other parts of the ship? If the procurement cost of the propulsion system is reduced, how much less cost-effective would the resulting propulsion system be, and what effects might this have for the idea of using the DD-21 electric-drive system as the basis for a common system for the fleet?
- **System Evolution.** Given the potential for electric-drive technology to evolve and improve over time, should the DD-21 be designed so that parts of the system can be changed over time, either in the construction process (i.e., forward fitting for later ships in the program) or during life-cycle overhaul and modernization (i.e., backfitting for earlier ships in the program)? What effect might this have on the time and funding needed to develop the DD-21's electric-drive system? Does the Navy's acquisition strategy adequately address this issue?
- **Latitude for Competing Dd-21 Industry Teams.** Does the Navy's acquisition strategy give the two competing DD-21 industry teams too much, not enough, or about the right amount of latitude in determining the features of the DD-21 electric drive system?
- **Potential for Common Fleet-Wide System.** Has the Navy structured the DD-21 competition to take into account the possibility that the DD-21 electric-drive system might become the basis for a common system for use by other Navy surface ships and submarines? Does the DD-21 competition require the two competing industry teams to select an electric drive system that would be suitable for a wide array of Navy ships? Do the electric-drive technologies being considered by the two industry teams include all those that might contribute to an optimal common Navy electric-drive system? If not, what effect might this have on the Navy's downstream ability to achieve the most cost-effective application of electric-drive on a fleet-wide basis? If there is a conflict between optimizing the DD-21 electric-drive system and optimizing

a common electric-drive system for the fleet, how should the Navy resolve the issue?⁷⁰

If it is decided early in the DD-21 development effort that the DD-21 electric-drive system will definitely become the basis for a common electric-drive system for Navy surface ships and submarines, then there are grounds for arguing that the DD-21 acquisition process should be structured so that consideration is given to optimizing the cost-effectiveness of electric-drive technology for the fleet, even if this adds costs to the DD-21 program or results in an electric-drive system that is not fully optimized for the DD-21 itself. If, however, it remains uncertain during the DD-21 development effort whether the DD-21 system will form the basis for a common system, policymakers may face a difficult decision in weighing the certain benefits of optimizing the cost-effectiveness of the electric-drive system for the DD-21 against the uncertain benefits of optimizing it for potential wider use in the fleet.

Given the competing motor technologies now being pursued, there are numerous potential strategies that can be pursued concerning the type of motor used in the DD-21 electric-drive system. The table below shows a variety of notional alternatives, but is not an exhaustive list.

⁷⁰ Questions regarding the relationship between the DD-21 electric-drive system and potential electric-drive systems for U.S. submarines were raised by Representatives Herb Bateman and Duncan Hunter at a June 27, 2000 hearing on submarine force structure and modernization issues held by the Military Procurement Subcommittee of the House Armed Services Committee. For a discussion, see Bohmfalk, Christian. First Electric Drive Submarine Not to Arrive in Fleet Until 2015. *Inside the Navy*, July 3, 2000. Representative Bateman posed questions on this issue in an April 6, 2000 letter to the Secretary of the Navy. For the text of this letter, see Text: Bateman Letter On Electric Drive. *Inside the Navy*, July 3, 2000.

Table 4. Selected Notional Options for Electric-Drive System on Dd-21 Class Ships, by Motor Type

First Ship/Earlier Ships in Program		Later Ships in Program
Forward fit during construction	Backfit during later overhaul	Forward fit during construction
Induction	none	Induction
Induction	none	Permanent magnet
Induction	Permanent magnet	Permanent magnet
Induction	none	Superconducting
Induction	Superconducting	Superconducting
Permanent magnet	none	Permanent magnet
Permanent magnet	none	Superconducting
Permanent magnet	Superconducting	Superconducting

Sources differed regarding the amount of technical risk associated with incorporating different versions of an electric-drive system into the first DD-21. The lowest-risk option would appear to be a system using an induction motor connected by a traditional horizontal shaft at the stern of the ship to a fixed-pitch propeller. Although the Navy does not consider the induction motor suitable for use on submarines, other components of this system could possibly form the basis for a common electric-drive system for the fleet.

This option could be pursued as part of a longer-term acquisition and modernization strategy for the DD-21 class in which later ships are built (and earlier ships are possibly backfitted with) a permanent magnet or superconducting motor. The potential cost-effectiveness of such an approach would depend on how it would alter costs and capabilities for both DD-21 class ships and (if the system forms the basis of a common fleet-wide system), subsequent classes of electric-drive-equipped ships.

With some amount of added risk – how much is not certain, but not necessarily enough to make the DD-21 program a high-risk effort – the lead ship’s system could include a permanent magnet motor rather than an induction motor. This option could lead to a streamlined approach for achieving a common electric-drive system under which all Navy electric-drive systems use an permanent magnet motor. In assessing this approach, policymakers would need to balance the risk associated with equipping the first DD-21 with a permanent magnet motor against the savings associated with developing, procuring, and supporting only one type of motor for both the DD-21 program and other classes of ships.

Although many sources agreed that there may not be enough time to develop an advanced propeller/stern configuration for the first DD-21 such as a podded propeller, they also agree that such a system could be developed within a few years and would offer both cost and capability advantages for the DD-21. This raises the issue of whether the baseline DD-21 design should be developed so as to facilitate the later incorporation of a more advanced propeller/stern configuration.

On June 14, 2000, Ingalls Shipbuilding – a division of Litton Industries and the leader of one of the two industry teams competing for the DD-21 – announced that it had selected the NNS-led electric drive industry team for the preliminary design of an electric drive propulsion system and will incorporate the NNS-led team’s permanent magnet motor design into its initial system design proposal for the DD-21.⁷¹

Virginia (SSN-774) Class Submarines. Electric-drive technology in some form could be installed on follow-on Virginia-class submarines, potentially on a boat procured within the next several years, depending on the configuration of the electric-drive system and the intensity of the Navy’s development effort.⁷² Navy officials testified in June 2000 that a nearer-term electric-drive system could be ready for a Virginia-class boat procured in FY2010.⁷³ Some industry sources suggested that it could be ready for a boat procured in FY2007 if a decision were made in the near term to pursue the option and adequate development funding was provided.

Given electric drive’s potential for achieving a substantial improvement in submarine quieting, a key question for policymakers concerns the urgency of achieving such an improvement: In light of current and projected antisubmarine warfare capabilities of potential adversaries, how quickly might such an improvement need to be incorporated into the U.S. submarine fleet?

⁷¹ Source: Litton Industries press release, June 14, 2000, entitled DD 21 Gold Team Selects Newport News Team for Permanent Magnet Motor Development. The Ingalls-led DD-21 team is known as the Gold Team. The press release stated: “The selection of the Newport News team’s PMM [permanent magnet motor] design is a result of the Gold Team’s independent, three-month evaluation of competing Permanent Magnet Motor proposals. Many factors including acquisition cost, life cycle cost, maintenance, manning, efficiency, [and] risk were analyzed and compared between the two motors. The final selection was accomplished by using a systems engineering process, as required by the DD 212 contract.”

⁷² For earlier discussions of the application of electric drive to attack submarines about the size of the Virginia class design, see Dade, Thomas B. Advanced Electric Propulsion, Power Generation, and Power Distribution. *Naval Engineers Journal*, March 1994: 83-92, and Dutton, Jeffrey L. Contrarotating Electric Drive for Attack Submarines. *Naval Engineers Journal*, March 1994: 45-50.

⁷³ Spoken testimony of Rear Admiral J. P. Davis and Rear Admiral Malcolm I. Fages to the Military Procurement Subcommittee of the House Armed Services Committee at a hearing on submarine force structure and modernization issues on June 27, 2000. For a discussion, see First Electric Drive Submarine Not to Arrive in Fleet Until 2015, op cit, and Bender, Bryan. US Navy Sets Sights on Electric Attack Submarine. *Jane’s Defence Weekly*, July 26, 2000.

In addition to a major improvement in quieting, some industry sources have suggested, and the Navy did not disagree, that electric-drive technology for submarines, if pursued ambitiously, has the potential for altering the stern of a Virginia-class submarine in a way that could reduce the procurement cost of the submarine (currently \$1.9 billion to \$2.0 billion) by as much as \$100 million. This is highly significant, because the Navy is seeking to increase the Virginia-class procurement rate in a few years from the currently planned rate of 1 per year to 2 or more per year, and any actions to reduce the procurement cost of the Virginia-class would make such an increase more affordable.

If the \$100-million figure above is roughly correct, electric-drive technology would represent a rare if not unique opportunity to make a change in the design of the submarine that reduces its procurement costs by such a large amount without reducing ship capability. Indeed, in more than a decade of searching for options for reducing submarine procurement costs, CRS has encountered no other single design change for a nuclear-powered submarine that could reduce procurement costs by such a large amount without reducing ship capability. Although numerous design changes have been suggested for the Virginia-class design (many of which have been or will be implemented), most will reduce the cost of the Virginia-class design by much smaller amounts (typically a few or several million dollars).

Pursuing electric-drive technology for submarines this ambitiously, however, would be very expensive: It could easily require hundreds of millions of dollars, or even more than a billion dollars, in research and development funding beyond the funding that the Navy has already programmed for development of electric-drive technology. As a consequence, even if the program succeeded in reducing the procurement cost of the Virginia-class design by \$100 million, it could be several years before savings in Virginia-class procurement costs fully recouped the up-front research and development costs of this development option. If the reduction in unit procurement cost turned out to be something smaller – for example, \$50 million instead of \$100 million – then the break-even point would be even farther in the future. Even if the break-even point were not reached until the procurement of the final units in the Virginia class, however, the technology would continue to act as a source of recurring savings on submarines procured following completion of Virginia-class procurement.

TADC(X) Auxiliary Dry Cargo Ships. Although often overlooked in discussions of electric-drive technology, the Navy’s planned TADC(X) class of auxiliary dry cargo ships, the first of which was procured in FY2000, is a near-term candidate for electric-drive propulsion. The Navy states: “The [TADC(X)’s] propulsion plant will either be diesel [with mechanical drive], gas turbine [with mechanical drive], or electric drive.”⁷⁴

⁷⁴ U.S. Navy Internet page, “ADC(X) Baseline Design,” version as of April 20, 2000, available at { <http://www.navsea.navy.mil/adcx/view/adcxbl.html> }.

As a large, slower-speed (20- to 26-knot),⁷⁵ non-combat ship now in procurement that is somewhat similar to a commercial cargo ship, it might be feasible and cost-effective to equip the TADC(X) with a currently-available European commercial electric-drive system similar to those now being used for cruise ships – a system employing a synchronous motor and possibly a podded propeller. This would raise at least two potential issues for policymakers:

- Would equipping the TADC(X) with a commercial electric drive system using a synchronous motor contribute to or detract from an effort to optimize the application of electric-drive technology to Navy ships?
- Should the TADC(X) be equipped with a European electric-drive system if that is the only kind of electric-drive system now available for the TADC(X)?

Jcc(x) Joint Command and Control Ships. Electric drive might similarly be a candidate for the four Joint Command and Control (JCC[X]) ships that the Navy plans to begin procuring in FY2004. The design of the JCC(X) has yet to be determined, but one possibility being considered is to build them to modified commercial-ship standards. If so, the JCC(X), like the TADC(X), might be a candidate for a commercial electric-drive system.

The operational requirements of the JCC(X), however, might require an electric-drive system with better quieting and shock resistance than a commercial system, in which case the ship might be a candidate for a more advanced military electric-drive system. If so, in light of the currently planned FY2004 date for procuring the first JCC(X), one possibility might be to equip this ship with a version of the electric-drive system that is developed for the DD-21. The question is whether the FY2004 procurement date for the first JCC(X) – one year earlier than the procurement date for the first DD-21 – would permit this.

LHA Replacement Ships. LHD-8, the first of the five LHA replacement ships, is to be built to a modified version of the basic Wasp (LHD-1) class design. The modifications include, among other things, the use of a hybrid propulsion plant consisting of a low-power electric-drive system for low-speed operations and a mechanical-drive system for higher-speed operations. The low-power electric-drive system will employ 1,000-horsepower electric motors using electricity produced by the same diesel generators that produce electrical power for the rest of the ship. The mechanical-drive system will be powered gas turbine engines (rather than the oil-fired steam turbines used on LHDs -1 through -7). During low-speed operations, the RPMs produced by the ship's electric motors will be transmitted to the propellers through the reduction gears of the ship's mechanical-drive system.⁷⁶ This hybrid

⁷⁵ The Navy's notional performance characteristics for the TADC(X) call for a maximum sustained speed of 20 to 26 knots. (U.S. Navy Internet page, "ADC(X) Baseline Design," op cit.) A speed of 20 knots would be comparable to the maximum sustained speeds of the ammunition and refrigerated stores ships that the TADC(X) is to replace.

⁷⁶ Source: Information provided to CRS via telephone by Ingalls Shipbuilding, the builder of LHD-1 class ships, July 24, 2000.

propulsion system is similar in some respects to the previously described diesel-electric/gas turbine-mechanical system used on Britain's Type 23 frigates.⁷⁷

The Navy is now assessing whether the second through fifth LHA replacement ships should be additional (and further-modified) LHD-1 class ships or a new-design amphibious assault ship known as the LHX. The further-modified-LHD option might, and the LHX option more certainly could, include a full electric-drive system.

In the case of the further-modified-LHD option, the issue for policymakers is how the benefits of incorporating full electric drive into some of the LHDs, if feasible, would compare to the costs of maintaining a fleet of LHDs with at least three kinds of propulsion systems (steam turbine/mechanical drive for LHDs -1 through -7, hybrid diesel/electric and gas turbine/mechanical drive for LHD-8, and gas turbine/electric drive for subsequent LHDs).

CVN(X) Aircraft Carrier. The Navy's March 1999 report to Congress on electric drive states that while electric drive is feasible for future aircraft carriers, mechanical drive would be more appropriate at this time – meaning that mechanical drive would be more appropriate for CVN(X)-1, the first of the Navy's planned class of next-generation aircraft carriers, which is to be procured in FY2006. The Navy report stated:

For a ship the size of an aircraft carrier, electric drive did not offer space or weight savings over a steam driven mechanical drive design with appropriately sized turbine generators. In addition, the studies found that the most affordable method to achieve the objective of increased electric generating capacity was to use mechanical drive with larger turbine generators.⁷⁸

The Navy's conclusion contrasts with a 1997 Naval Research Advisory Committee (NRAC) report on the CVN(X) that strongly endorsed the idea equipping the CVN(X) with electric-drive technology.⁷⁹ Although the Navy's March 1999 report reflects two years of additional information and study of the issue, in light of the 1997 NRAC study and the potential for electric-drive technology to evolve and improve, policymakers may review the Navy's 1999 conclusion periodically (e.g., with the procurement of each carrier) to determine whether it remains valid.

⁷⁷ See the background section for the description of the Type 23 propulsion system.

⁷⁸ This passage is taken from the executive summary of the Navy's report, which is printed in its entirety in the background section of this report.

⁷⁹ Naval Research Advisory Committee. *CVX Flexibility*. Washington, 1997. 80 p. (Report to Assistant Secretary of the Navy (Research, Development and Acquisition), NRAC 97-1, October 1997.) The conclusions of the NRAC report on this point are also referenced in Davis, Jacquelyn K. *CVX, A Smart Carrier for a New Era*. Washington and London, Brassey's, 1998. (A publication of The Institute for Foreign Policy Analysis, Inc., in association with the Fletcher School of Law and Diplomacy, Tufts University) p. 45, 58, and in Walters, J.D., et al. Reexamination of Superconductive Homopolar Motors for Propulsion. *Naval Engineers Journal*, January 1998: 107-116.

Coast Guard Deepwater Cutters. The Coast Guard commissioned two studies, both delivered in 1998, that examined various propulsion options, including electric drive, for cutters procured under the Deepwater project. These reports, however, did not come to any firm conclusions or recommendations regarding the kind of propulsion system that might be best suited for this ship.⁸⁰

In 1998, the Navy and the Coast Guard issued a joint policy statement setting forth a new “national fleet concept” under which the two services would seek to coordinate their activities more closely in various areas, including equipment procurement. The document states:

As we enter the next millennium... the Navy and Coast Guard, together, must deploy forces with greater flexibility, adaptability and affordability....

Because of incompatible equipment, mutual logistics support has proven difficult, as has the ability to exchange near real-time intelligence and information. *As partners in maritime security, our approach should stress commonality wherever appropriate, from shipboard propulsion systems to aircraft components to training standards.*

The National Fleet has two main attributes. First, the fleet is comprised of surface combatants and major cutters that are affordable, adaptable, interoperable, and with complementary capabilities. Second, whenever appropriate, the fleet is designed around common equipment and systems, and includes coordinated operational planning, training and logistics....

The Navy and Coast Guard will work together to build a National Fleet of multi-mission surface combatants and cutters to maximize our effectiveness across all naval and maritime missions. The Navy and Coast Guard will coordinate surface ship planning, information systems integration, and research and development, as well as expand joint concepts of operations, logistics, training, exercises and deployments. The Coast Guard and Navy will work together to

⁸⁰ Krull, R. D. *Propulsion Systems Survey for the USCG Deepwater Surface Platform*. Stevensville (MD), 1998. 23 p. (Report No. CG-D-13-98, Final Report, February 1998, Prepared for U.S. Department of Transportation, United States Coast Guard, Acquisition (G-A), and U.S. Coast Guard Research and Development Center, available to the U.S. public through the National Technical Information Service, Springfield, Virginia); Krull, R. D., and H., Robey. *Integrated Electric Drive Application to USCG Deepwater Project*. Stevensville (MD)?, 1998, 13 p. (Prepared for U.S. Coast Guard Research and Development Center, Groton, CT, 21 August 1998, Contract No. DTCG39-94-D-E56616, Delivery Order DTCG39-97-F-E00348) The first report provides an overview of various potential prime movers, transmission systems (including electric drive), and propellers and other propulsors. The report states that “a number of currently operating propulsion system concepts that would be new to the Coast Guard, such as water jets, podded propulsors, and AC electric drives[,] are candidate technologies.” The report also notes the potential advantages of various options (including electric drive) for meeting certain mission requirements of a Deepwater cutter. The second report provides a general discussion of electric drive and potential advantages and disadvantages, and a description of the Navy’s IPS program.

acquire and maintain future ships that mutually support and complement each service's roles and missions.⁸¹

The national fleet concept, with its emphasis on commonality, raises a potential issue for policymakers concerning the possibility of using electric-drive on the cutters that are to be procured under the Deepwater project. Equipping these cutters with electric-drive could produce ship capability and life-cycle cost benefits for the Coast Guard similar to those that electric-drive technology will produce for the Navy,⁸² and potentially improve economies of scale for both the Navy and Coast Guard in the production, operation, and life-cycle support of ship propulsion systems.

In assessing the feasibility of this notion, one issue to address would be the size of the cutters' propulsion plant. The cutters to be procured under the Deepwater project will likely be much smaller than the DD-21 design. The cutter might have a full load displacement of less than 5,000 tons, while the DD-21 might have a displacement of about 12,000 tons. It is not clear that an electric-drive system designed for the DD-21 or other large Navy ships could be easily scaled down or otherwise modified to produce a system suitable for a cutter-sized ship. If the Navy's electric-drive system employs a modular architecture in which smaller modules are combined to create a system with the requisite power, scaling the system down to a size appropriate for a Coast Guard cutter might be made easier. If some elements of the system needed to be changed to make the system suitable for a cutter, policymakers would face an issue of whether the design and development costs for the changed components should be paid for by the Coast Guard, the Navy, or some combination.

A second issue concerns the schedule for the Deepwater program. Under the Coast Guard's plans, the first Deepwater cutter is to be procured in 2002 – three years before the DD-21. The three industry teams now competing for the Deepwater project, moreover, have completed much of the initial work on their proposed Deepwater cutter designs. Incorporating electric-drive into the first Deepwater cutters might thus require restructuring the Deepwater program to delay the start of cutter procurement and have the industry teams redo much of their initial design work.

This would delay the introduction of the new cutters into the Coast Guard's fleet – something the Coast Guard strongly wants to avoid, given the advanced age, limited capabilities, and high operating costs of its current cutters. It would also increase research and development costs for the Deepwater project – something the Coast Guard also strongly wants to avoid, given the Coast Guard's limited acquisition budget and an already-significant challenge in identifying adequate funding for the Deepwater project as currently conceived.

⁸¹ NATIONAL FLEET — A Joint Navy/Coast Guard Policy Statement. Washington, 1998. (September 21, 1998) 2 p. Emphasis added.

⁸² The 1998 NATO report that endorsed electric drive as feasible and viable focused on a notional design for a 4,000-ton frigate – a ship potentially about the same size as the Deepwater cutter.

Another approach would be to build the first few Deepwater cutters as mechanical-drive ships, then build later cutters to a modified design that incorporates electric drive. This would resolve the issue concerning the Coast Guard's desire to begin procuring cutters in 2002, but would still leave the issue of who should pay for any design and development work that would be needed to modify the Navy's electric-drive system to make it suitable for use in the Coast Guard's new cutters.

In addition, given the potential impact of electric drive on the overall design of a ship, the amount of ship redesign needed to optimize the application of electric drive to later ships in the program could be extensive – and thus expensive. Redesigned ships might also be delivered later, slowing the pace at which new cutters are introduced into Coast Guard service. The alternative of simply incorporating electric drive into a baseline Deepwater cutter originally designed for mechanical drive would likely result in a ship that does not achieve the full benefits of electric drive.

Building later ships in the production run with electric drive would also create an issue regarding a lack of propulsion-equipment commonality among the Coast Guard's new cutters. This would add complexity and possibly cost to the Coast Guard's strategy for life-cycle operation and support of the new cutters.

Another issue that may arise concerns the composition of the industry teams that are competing for the Deepwater and DD-21 programs. The teams competing for these two programs contain differing combinations of firms, which may make it difficult to transfer electric-drive technology from the DD-21 program to the Deepwater project without compromising “firewalls” that are intended to prevent transmission of competition-sensitive information between teams competing for the same program. In addition, one source suggested that the idea of incorporating electric drive into the Deepwater cutters could itself add political uncertainty to the Deepwater project, reducing industry confidence in the program.

Potential questions for policymakers include the following:

- How necessary is it to procure the first Deepwater cutter in 2002? If procurement were delayed to 2005, how would this affect Coast Guard fleet capabilities and operational costs? What would be the effect on the Deepwater project?
- How do the potential ship-capability benefits of incorporating electric-drive into Deepwater cutters compare with the benefits of incorporating it into a Navy surface combatant like the DD-21?
- How do the potential savings of incorporating electric-drive technology into the new cutters (from reduced life-cycle operating costs and commonality with the Navy in the production, operation, and support of ship propulsion equipment) compare with the potential additional costs of this option (for design and development work, and potentially due to loss of commonality in propulsion equipment across all the new cutters that are procured)?

- How significant a factor should the principles set forth in the Navy/Coast Guard national fleet policy statement be in considering the issue of the new cutters' propulsion equipment?