Navy and Industry Pursuing New Power and Propulsion Methods

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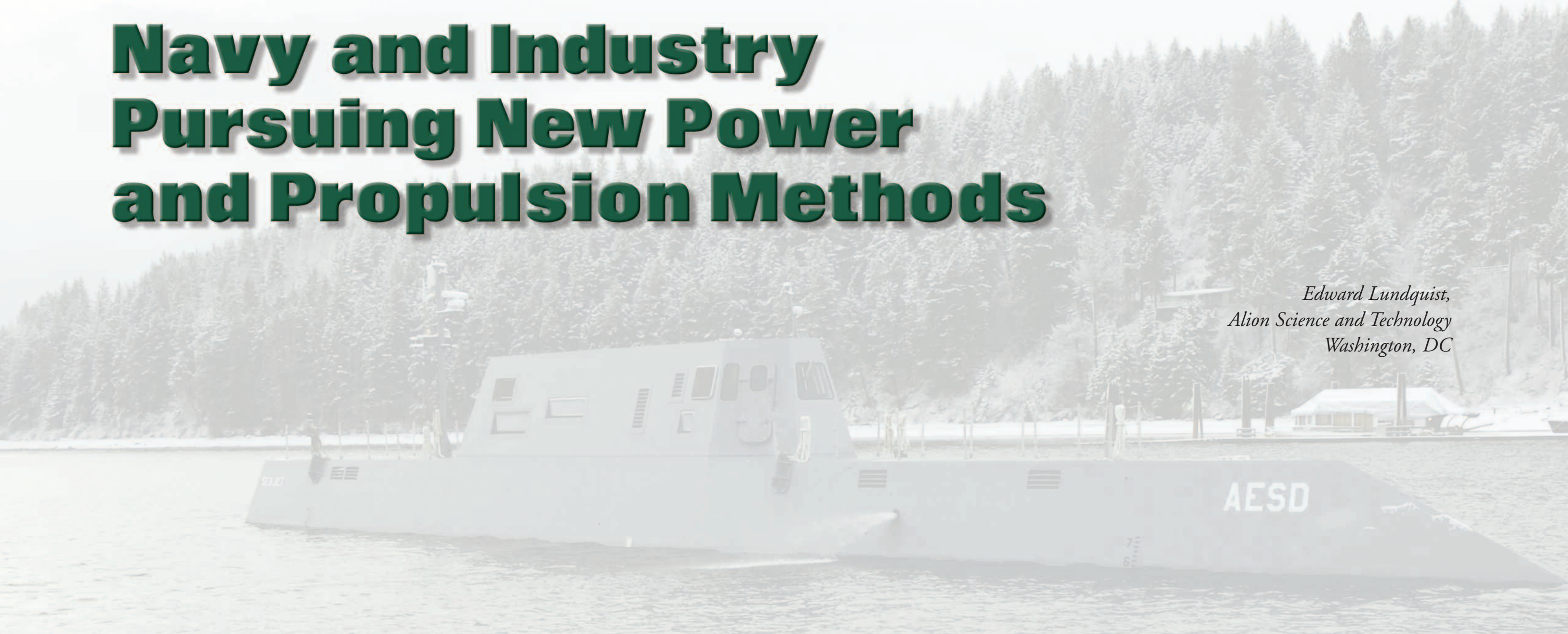

The Navy is testing new concepts in power generation, conversion, and distribution to make ships more efficient, economic, and combat-effective. Ships being developed in both the near term and long term will have a variety of newly designed propulsion systems depending on their size, mission, and ship characteristics. This article discusses some key technologies on the horizon.

ALL-ELECTRIC INTEGRATED PROPULSION

An integrated power system (IPS) is an all-electric architecture, providing electric power to the total ship with an integrated plant. IPS enables a ship's electrical loads, such as pumps and lighting, to be powered from the same electrical source as the propulsion system (e.g., electric drive), eliminating the need for separate power generation capabilities for these loads.

To meet the increased power demands for new sea-based weapon systems, next-generation surface combatants, such as the DDG 1000 *Zumwalt*-class of guided missile destroyers (see Figure 1), will feature all-electric propulsion and an entirely new way of distributing power for propulsion, ship service, and combat capability. *All-Electric Propulsion* is a promising technology for both naval and commercial marine applications. On the DDG 1000, power will be generated by two large gas turbine generators and two smaller ones. By using efficient power management, power is available to handle all of the electric loads throughout the ship, including potential future power-hungry weapons such as rail guns or directed energy weapons.

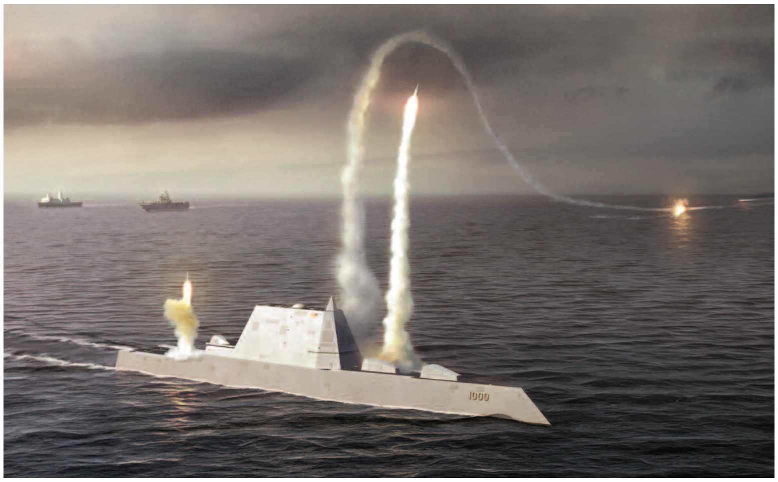

Figure 1. An artist's rendering of the *Zumwalt*-class destroyer DDG 1000, a new class of multi-mission US Navy surface combatant ship designed to operate as part of a joint maritime fleet, assisting Marine strike forces ashore as well as performing littoral, air and sub-surface warfare. (Photo courtesy of US Navy)

The combat value of an electric ship goes well beyond weapon capability and capacity. There are significant efficiencies and redundancies. At full power, DDG 1000 will achieve speeds up to 30 knots. If one of the main turbines is lost, the plant can be isolated and still achieve 27 knots. Since a warship usually cruises at reduced power once it has arrived on station, normal station-keeping can be accommodated with the two small turbines to save fuel and reduce radiated noise. The power previously trapped in the propulsion train can now be directed to enhance combat capability and mission flexibility. At lower speeds, *Zumwalt* has a surplus of power that can be made available as needed. Further advantages include the elimination of maintenance-intensive and high-temperature auxiliary steam systems, reduced noise and vibration, and better fuel efficiency.

Among the major advantages of electric drive for naval ships is that the prime movers, whether gas turbines or diesels, do not need to be located in a central machinery space or mechanically connected to the propeller shaft as with traditional propulsion systems. Instead, the engines can be located anywhere in the ship, distributed throughout the hull, and connected to generators to supply power. This power can be fed to a central bus that can be used for propulsion.

An all-electric integrated propulsion system enables more design flexibility in terms of engine placement. For example, the engines can be placed in the bow, stern, or even in the superstructure for smaller engines. One of the advantages of distributed power in a warship is survivability. If an engine incurs

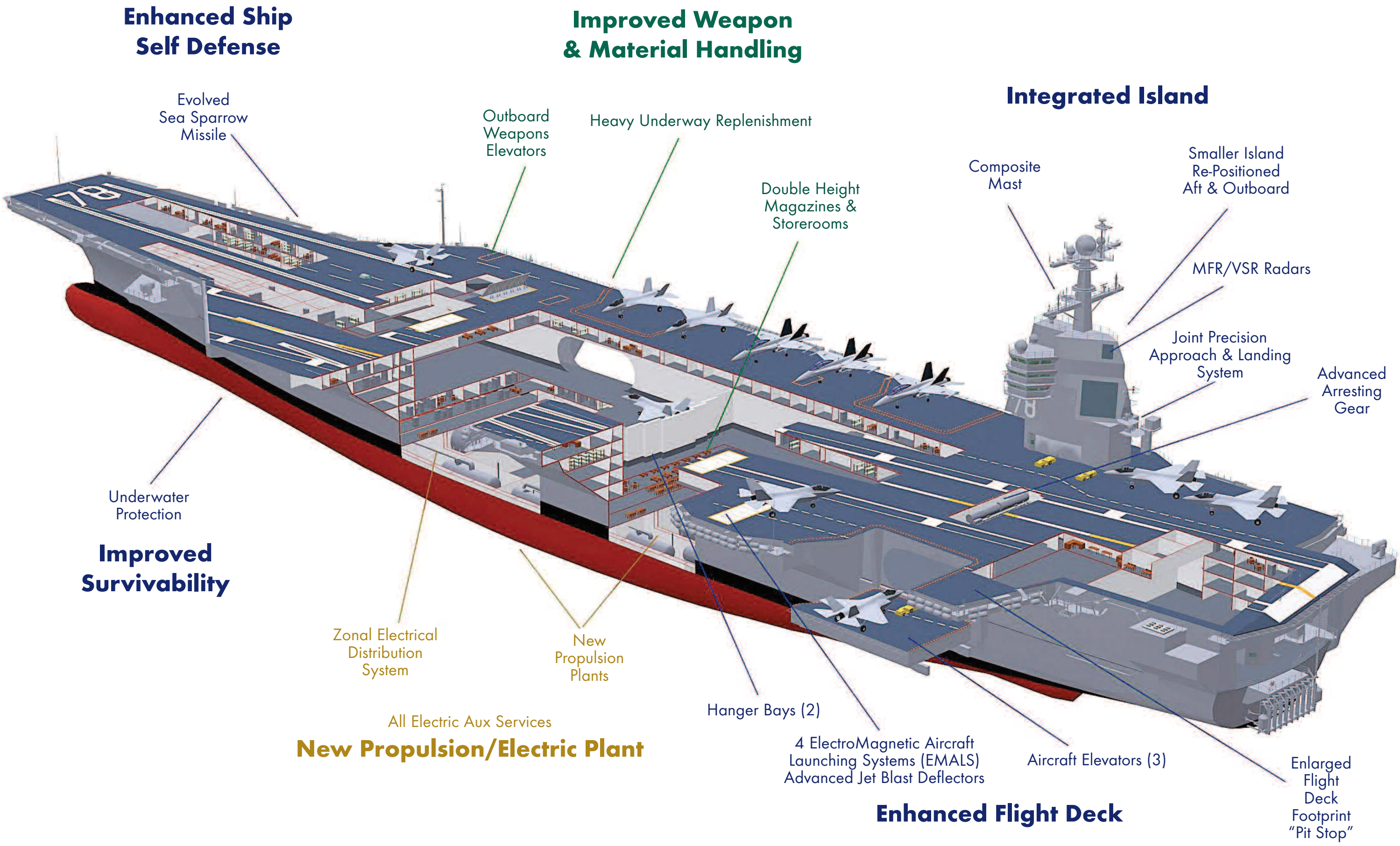

Figure 2. A conceptual rendering of CVN 78, the first of a new generation carrier design (CVN 21) for the US Navy, underway at Northrop Grumman Newport News. Innovations for the next-generation aircraft carrier include an enhanced flight deck with increased sortie rates, improved weapons movement, a redesigned island, a new nuclear power plant, and allowance for future technologies and reduced manning. (US Navy illustration courtesy of Northrop Grumman Newport News Shipbuilding)

damage or is incapacitated in one part of the ship, that part of the distribution system can be isolated while power can still be generated and distributed throughout the rest of the system. The DDG 1000 will be powered by Rolls-Royce MT30 gas turbines, which is based upon the Rolls-Royce "Trent" engine that powers the Boeing 777 airliner. The aviation version of the engine has a demonstrated reliability of 99.98%. The 'marinized' version of the MT30 has 80% commonality with the Trent 800 but is shock-mounted and has different blade coatings for operation in a saltwater environment. This engine is also serving today aboard the new Littoral Combat Ship *USS Freedom* (LCS 1). *Zumwalt* will also have a smaller gas turbine, the Rolls-Royce 4500.

DDG 1000 power generators produce 4,160 volts alternating current (AC), which is rectified to direct current (DC) that allows ship service power distribution to be tailored to the ship's needs. There are three primary advantages to DC. First, DC uses solid state power conversion that supplies loads which are converted back to AC and is a cleaner way to supply power. Secondly, many of the combat systems' loads are DC. Finally, it enables power to be shared and auctioned. DC enables uninterrupted power even in the occurrence of a casualty.

The DDG 1000 will employ fixed pitch propellers. Controllable pitch propellers and their associated complex hydraulics are not required since the motor, and thus the shaft, can be electrically reversed. But novel approaches to propulsion are being considered for future combatants.

Other new naval ships are also adopting integrated electric power systems. The next-generation CVN 21 aircraft carrier, the *USS Gerald Ford* (see Figure 2), will have a newly designed nuclear power plant and all-electric systems and propulsion. The next amphibious assault ship, the *USS Makin Island* (LHA 6), will feature a combined gas turbine and electric propulsion system.

The surface combatant IPS propulsion engineering development model (EDM) for DDG 1000 is being tested at the Land-Based Test Site (LBTS) at the Ships Systems Engineering Station in Philadelphia. The test site has been used to evaluate different configurations and motors. The test program validates key system metrics such as torque, speed and power output, and specific fuel consumption for the various configurations.

The Navy has tested the 18-megawatt (MW) advanced induction motor (AIM), which will be the baseline for DDG 1000, produced by Alstom at the LBTS. This is essentially the same system installed on the Royal Navy's new Type 45 destroyer, the *HMS Daring*, which has just been commissioned. The IPS features Integrated Fight through Power (IFTP), a fully automated DC Zonal Electric Distribution System (DC ZEDS) that provides flexible, reliable, high quality power to all shipboard loads. Other configurations are also being tested. The IPS system is fully automated with little operator intrusion. The testing at the LBTS will validate that the DDG 1000 IPS will automatically take appropriate corrective action if there is a malfunction or casualty without the input of an operator.

Engineers at the LBTS have also tested a 36-megawatt permanent magnet motor (PMM). PMM has greater power density than the AIM and may be used in future ships.

Many studies were performed on different combinations of gas turbines. The purpose was to avoid development of new gas turbines that were not qualified and in service or on their way into service.

Although there are advantages to distributing the power system throughout a warship hull, the size and weight of the various components has usually necessitated keeping the propulsion equipment low in the ship for stability reasons. The DDG 1000 engineering plant layout is relatively conventional because of the air intake, exhaust, and drive arrangement.

DRS Technologies and General Atomics Electromagnetic Systems are developing a hybrid electric drive which permits a smaller service gas turbine to power a permanent magnet motor that can power the ship at slow or “loiter” speeds. Using a smaller turbine can result in significant fuel savings. Furthermore, the motor can be reversed to function as a generator when propulsion gas turbines are online.

Overall, integrated electric drive offers ship designers and operators a plant flexibility that does not exist with mechanical drive systems. However, trade studies must be used to select the appropriate power and propulsion system for each ship.

There are some ships with partial electric drive or hybrid electric drive mechanical drive systems. These include the operational Type 23 frigates; the European Multi-Mission Frigates (FREMM), a joint program between France and Italy, which are now in construction for France, Italy, Morocco and Greece; and the amphibious assault ship *USS Makin Island* (LHD 8), now undergoing trials.

Despite the advantages, there are not a lot of electric drive warships in service. The new generation of electric ships has yet to prove themselves. The DDG 1000, Royal Navy Type 45, and T-AKE propositioning ships are examples of all-electric warships, but they are still in the design phase, under construction, or just entering service. Even though there is significant interest in electric drive systems, there are only a relatively small number of ships actually under construction and in operation.

SUPERCONDUCTING MOTORS

American Superconductor and Northrop Grumman have recently tested a 36.5-megawatt high-temperature superconductor (HTS) ship propulsion motor at the LBTS. The motor uses HTS wire that can carry 150 times more power than copper wire used in more conventional motors. The advantage is more compact propulsion systems which have greater power density. Superconducting wire can carry more current and generate higher magnetic fields in very small areas and thus can result in a significantly smaller motor. In other words, more power is available from smaller, lighter motors. That means Navy ships can carry more fuel and munitions and have more room for crew’s quarters and weapon systems.

General Atomics’ (GA) superconducting DC homopolar motor for propulsion applications is small and light compared to traditional and superconducting AC motor systems. This motor uses low-temperature supercooling that employs gaseous helium to maintain the superconducting wire within the motor at 5 Kelvin, which is almost absolute zero. Since some materials are much better conductors at very cold temperatures, and with virtually no electrical resistance supercooled conductors make for much more efficient motors. A comparable high-temperature supercooled system operates between 40 and 75 Kelvin, depending upon the technology chosen. Refrigeration at higher temperatures is easier, but the high-temperature superconducting material is not as easy to produce and is much more expensive than the superconducting niobium-titanium wire in the low-temperature motor. Niobium-titanium wire is the most widely used and available superconducting wire in world-wide commercial applications.

GA has built a 5,000 horse-power (HP) motor which is 4.5 feet in diameter. This technology is slender, light, and fuel-efficient and can be more readily adapted to propulsion pod applications.

Additionally, while superconducting AC motors have similar costs to the superconducting DC motor, there is no need for power inverters and the associated electronics to switch DC to AC.

Propulsion Pods

Most marine motor applications are located within the hull and coupled to a shaft to turn a propeller or waterjet impeller. Electric power can also be used for propellers or waterjets but can also power propulsion pods, which can be located outside the hull.

Pods provide better maneuverability to ships entering and leaving port or maintaining a precise station. With a significant amount of propulsion equipment located outside the hull, more room is available inside the ship for other purposes. Also, the signatures could be mitigated if the propulsion system was isolated inside the hull.

Cruise ship pod systems, such as “Mermaid” from RRAB (a joint venture with Rolls-Royce AB and Alstom) and ABB’s “Azipod” systems, can rotate 360 degrees and eliminate the need for rudder assemblies. With a pod, the motor is in the pod, while an azimuthing thruster has the motor located in the hull. The Royal Navy’s *Echo*-class of survey vessels uses electric azimuthing thrusters. Pods were considered for *Zumwalt*-class ships but ruled out because of their size.

The US Navy has used Small Water Plane Area Twin Hull (SWATH) ships for research and surveillance. These catamarans have long and slender motors and other propulsion equipment located in the submerged cylindrical buoyant hull sections, but prime movers can be mounted above the waterline. ThyssenKrupp’s Nordseewerke has built the SWATH research vessel *Planet* for the German Federal Office of Defense Technology and Procurement. *Planet* will assess new propulsion technologies and evaluate the sea keeping characteristics of the SWATH hull form. Its electric propulsion enables it to test mine detection and undersea warfare systems and countermeasures.

Siemens in Germany is finding improved power availability and system responsiveness with high-temperature superconductors for podded waterjets applications. Siemens is also developing fuel cell technology for ship propulsion.

Figure 3. **The AESD *Sea Jet*, funded by the Office of Naval Research, is a 133-foot vessel located at the Naval Surface Warfare Center Carderock Division. (Photos by Mr. John F. Williams and provided courtesy of US Navy)**

Waterjets

While not a new form of propulsion, waterjets have not been used on larger ships until recently. They present some clear advantages for warships. Waterjets deliver rapid acceleration and can sustain high speeds. Waterjet-powered ships are extremely maneuverable and can stop quickly. They offer simplicity. The flow is constant in a single direction. Engine loading is constant, regardless of vessel speed, and waterjets do not overload the engines. There may be no need for a gearbox. Astern propulsion is applied by means of deflectors that divert the jetstream forward. Precise station keeping can be maintained with waterjets.

There are many advantages of waterjets. The most prominent advantage is the shallow draft of the system. Waterjets do not have appendages (such as propellers, shafts and struts, or rudders) that extend below the waterline. This minimizes the risk of damaging the propulsion gear from grounding or from hitting a submerged object, and it also reduces the maintenance requirements. As a result the boats can operate close to the shoreline, land on a beach for deployment of troops or equipment, or even run over submerged logs or sandbars without damaging the propulsion equipment. In addition, floating debris (such as ropes, nets, or weeds) does not pose much of a risk to the system particularly at high speed. Even though these items may be drawn into the jet unit at slow speeds, they are unlikely to cause damage and can easily be removed.

Waterjets are reliable. Like propeller-driven ships, there is still a shaft but it turns the pump impeller at a constant speed as compared to a much larger propeller. Drive shafts, gear boxes, and engines receive less stress, thus prolonging their service lives. The entire propulsion system requires less maintenance.

Waterjets are more efficient at higher speeds, particularly in multiple drive installations such as catamarans. With no underwater appendages, there is no increase in hull resistance as speed increases or more drives are added. Efficient operation can also be achieved over a broader range of speeds compared to propellers. Waterjets cannot overload an engine due to excess boat weight, towing, or extreme seas because they operate independently of the body of water under a boat.

A fast vessel needs a relatively higher amount of power than a slow vessel, and waterjets can provide a relatively large amount of power despite their relatively small size. Conventional propulsors would require relatively large propeller diameters.

A clean hull design, free of appendages, delivers greater speed. Drag resistance increases significantly as ship speed increases. Therefore, the absence of appendages becomes increasingly important as ship speed requirements increase.

The Office of Naval Research (ONR) uses an experimental 130-foot-long craft called the Advanced Electric Ship Demonstrator (AESD) to test various waterjet-based propulsion configurations at the Navy's Acoustic Research Detachment at Lake Pend Oreille, Idaho. ONR engineers achieved improved efficiency and maneuverability with a smaller, lighter propulsion system while reducing noise at the same time. Named *Sea Jet* (see Figure 3), the craft is essentially a quarter-scale model of the DDG-1000 destroyer. It has been used to test an AWJ-21 underwater discharge waterjet from Rolls-Royce Naval Marine, Inc., to validate better propulsive efficiency, reduced acoustic signature, less drag, and better speed as well as improved maneuverability for future surface combatants by eliminating rudders, shafts, and propeller struts.

Figure 4. ***USS Freedom*** **(LCS 1) is the first US Navy Littoral Combat Ship in an entirely new class of Navy surface warships. The ship is designed for littoral, or close-to-shore, operations and to provide access and dominance in coastal-water areas. (Photo provided courtesy of Lockheed Martin)**

Sea Jet has also been employed to demonstrate the General Dynamics Electric Boat RIMJET propulsor, which is a podded system that features a permanent magnet motor to power a propeller in the rim, rather than the hub, of the pod. The system uses sea water for coolant, which eliminates the typical elaborate cooling system consisting of pumps, piping, and heat exchangers.

ONR has also developed an Advanced Hull Form Inshore Demonstrator (APHID) which is testing a complete electric podded propulsion system. The Rim-Driven Propulsor Pod (RPD) uses a Pulse-Width Modulated (PWM) motor drive system mounted on the Hybrid Small Waterplane Area Craft (HYSWAC). Called *Sea Flyer*, the HYSWAC is built from a modified Navy Surface Effect Ship and uses a Vericor TF-40 gas turbine prime mover. Sea Flyer features an underwater lifting body ship that combines the high-speed capabilities of a hydrofoil and the rough-water stability of a small waterplane area twin hull (SWATH), so it delivers higher speed and improved stability over comparably sized vessels.

Cost can be an initial disadvantage of waterjets. They are expensive to purchase and maintain. Waterjets are made from costly stainless steel, which is more expensive than other propulsors that are typically made from copper alloys. However, waterjet lifecycle costs are relatively lower. Waterjets are less prone to impact damage, and reduced engine stress results in less engine maintenance and longer engine life.

The Littoral Combat Ships (LCS) will employ waterjets. Waterjets were chosen for LCS to provide high speeds in shallow waters, where the LCS will operate to combat asymmetric anti-access threats in the littoral regions of the world. Two variants of LCS are being built. Lockheed Martin has delivered the *USS Freedom* (see Figure 4), a semi-planing monohull design built at Marinette Marine in Wisconsin. General Dynamics is building a trimaran, the *USS Independence*, at Austal USA in Mobile, Alabama. Both will have diesels and gas turbines, and both will employ waterjets. The General Dynamics LCS has four steering and reversing waterjets, while the Lockheed Martin LCS has two steering and reversing and two booster jets. Both ships displace about 3,000 tons and up to 4,000 tons fully loaded. This will make the two LCS combatants the largest naval waterjet-powered warships.

While the two versions have taken different naval architectural approaches to the mission, both "seaframes" will carry mission modules that can be reconfigured to adapt to each ship's combat mission assignment.

USS Freedom is powered by two Rolls-Royce MT30 36 MW gas turbines and two Fairbanks Morse Colt-Pielstick 16PA6B STC diesels. The seaframe is based on the Fincantieri-built, Donald Blount-designed high-speed yacht *Destriero*, which holds the record for the fastest transatlantic crossing (60 knots). The 378-foot *Freedom* has a steel hull with aluminum superstructure. The two 36 MW gas turbines and two diesel engines power four large Rolls-Royce Kamewa waterjets. Four Isotta Fraschini Model V1708 ship service diesel generator sets provide auxiliary power.

USS Independence, the slender stabilized trimaran monohull built by the General Dynamics team, has an overall length of 418 feet, maximum beam of 93 feet, and full load displacement of 2,637 tons. The seaframe is based on Austal's design for the Benchijigua Express passenger and car ferry. Two General Electric LM2500 22 MW gas turbines and two MTU 20V8000M90 9100 kW diesel engines are the prime movers, powering four large steering and reversing Wärtsilä-Lips 2 X LJ160E and 2 X LJ150E waterjets. With all propulsion flat out, the Wärtsilä-Lips waterjets together expel roughly 27,000 gallons of seawater per second exiting from the jet nozzles at a speed around 90 mph. The trimaran variant built by General Dynamics will also have a retractable azimuth thruster.

CONCLUSION

One design is not optimum for all situations. Cruise ships with large portions of their itineraries at low power benefit from electric drive. Fast ferries, which go to full throttle as soon as they clear the breakwater and remain at full throttle until they reach the next port, would be at a disadvantage with electric drive. There are advantages to a mechanical drive system. Mechanical drive systems are more efficient compared to electric drive systems in terms of their ability to transmit energy from the prime mover to the propulsor. For example, the mechanical drive is estimated to transmit approximately 98% of the energy from the prime mover output shaft to the propulsor. The electric drive is estimated to transmit between 91% and 93%.

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