ASNE EMTS Symposium (23-24 May 2012)

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Advanced Shipboard Energy Storage System

ABSTRACT

RCT Systems led a team that included Creative Energy Solutions, and NDI Engineering in the development of an Advanced Energy Storage Module (ESM) for the Office of Naval Research (ONR) under a Broad Agency Announcement (BAA) contract for a DDG 51 Fuel Efficiency Demonstrator. The project demonstrated a modular 600kW ESM in December 2010. These modules could be combined into a 3 MW system to allow DDG 51 single generator operations, providing full ship backup power for up to 10 minutes with significant fuel savings. These savings are dependent on the ship operating profile. The BAA assumed 4,000 hours per year per ship of single generator operations. Based on that estimate, the system could facilitate savings of ~8000 BBL of Fuel/ship/year, or up to ~ $1.3M/ship/year in direct fuel savings [at Jan 2012 DLA Fuel Rates of $160/bbl]. This equates to ~30% direct savings in the ships electric plant fuel usage during peace time cruise and an 8% savings in overall ships fuel usage based on Navy Incentivized Energy Conservation (I-ENCON) reports. DoD has mandated the use of Fully Burdened Fuel Cost (FBFC) in all future acquisition decisions. FBFC savings could be as high as $3-5M/ship/year in FY-12 Dollars. We estimate that hardware costs alone could be recouped in ~2 years based on FBFC savings. Navy testing at NSWCCD SSES DDG-51 Land Based Engineering Site (LBES) is ongoing, and it is planned to install the ESM in a DDG-51 Class ship in summer/fall of 2012 for an at sea demonstration. The Navy is currently determining the total energy required to be available to satisfactorily de-risk single generator operations on DDG-51 Class ships.. While designed for DDG 51, the modular system is potentially adaptable to all Navy and commercial ships, and supports the Next Generation Integrated Power System (NGIPS) Architecture.

INTRODUCTION

Over the last decade there has been increasing concern about Energy Security, our reliance on foreign oil, and the increasing cost burden that fuel imposes on our military operations. The Defense Science Board (DSB) has addressed this issue over the years. Specifically, in 2001 the Task Force Report "More Capable Warfighting Through Reduced Fuel Burden" and the more recent (2008) report "More Fight - Less Fuel" provided specific recommendations that the services should take to reduce fuel usage. In response, DoD Components have initiated specific programs to address the need to reduce our reliance on petroleum based fuels. In October 2009 at the Naval Energy Forum, SECNAV Ray Mabus laid out 5 ambitious Energy Related goals, including changing the acquisition process to consider the lifetime energy cost of the system. The Navy also chartered Task Force Energy which was led by OPNAV N45 (then RADM, now VADM Phil Cullom, USN), to address our heavy reliance on foreign oil and the need to develop alternatives to ensure our armed forces are both good stewards of the environment and are able to respond when called upon by national command authority.

In 2007, pre-dating the recent DoD and DoN actions, ONR issued BAA 07-029 "Fuel Efficient and Power Dense Demonstrator for The *USS Arleigh Burke (DDG 51) Flight IIA* Class Ship," with the intent "….to leverage … (S&T) investments to investigate and demonstrate new technologies capable of reducing fuel consumption, improving power conversion efficiency, and to a lesser extent, increase installed power generation density …"

While DoD Components have been incentivized to operate more efficiently and decrease fuel usage, fuel costs have been increasing because

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of the volatility in the market. The practice of trail shaft operations has been adopted to reduce propulsion fuel usage when feasible. However in the case of the ships service electrical plant, the need for assured electrical power requires the operation of redundant generators which has limited the ability of Commanding Officers to operate the electrical plant at optimal efficiency.

In the case of the *Arleigh Burke Class* Destroyers, like the CG 47 *Ticonderoga Class* Cruisers and earlier *Spruance* and *Kidd* classes, ship service electrical power is provided by 3 installed gas turbine generator sets (GTG). While the DDG 51 Class peace time ship electrical load is less than the generator rating for a significant fraction of operating time, standard practice is to have two GTGs on line at all times to ensure continuity of service should there be a system fault, or casualty to one of the GTGs.

While saving fuel is an important consideration, loss of power due to a system fault, or casualty to that single GTG is unacceptable and would mean going dead-in-the water (DIW) with the consequent loss of all ship systems, including weapons, sensors, communications, navigation, as well as propulsion and auxiliary systems, except those which have battery backup to prevent system damage and simplify restart. Because the restart time for critical sensitive electronics can be considerable, many systems have dedicated uninterruptible power supplies (UPS) that are found throughout the ship, adding battery systems that take up space, weight and require on-going maintenance. The potential for loss of power is the primary reason that standard procedures require 2 engine operations.

Gas turbine engines are most fuel efficient (lowest specific fuel consumption [SFC] in pounds of fuel burned per horsepower-hour) when operating at or near full power. When a ship operates with two partly loaded generators providing power they are less efficient, with higher SFC (i.e. burning more fuel). Therefore, operating one GTG that is highly loaded can result in significant fuel savings. For the purposes of the BAA, the assumed average ships electrical load was 2525 kW and 4000 hrs/year operation. A representation of the potential savings is shown graphically in Figure 1 below.

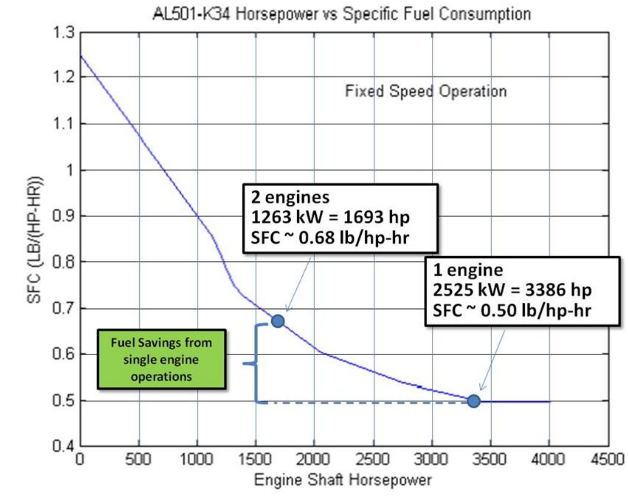


FIGURE 1. Fuel Savings from Single vs Two Engine operation

The calculated annual fuel savings at this operating point is nearly 8,000 BBL of fuel, or $1.28M at $160/BBL at the current DLA Energy rate charged the Navy (Jan 2012). Actual operating hours could be lower perhaps 2,500-3000 hours/year (based on recent operational data). However, as the delivered cost of fuel continues to increase the dollar savings will also increase. These figures represent >25% improvement in overall electric plant fuel efficiency.

Ships force can calculate fuel savings in Gal/Hr (GPH) using a nomograph for the 501-K34 fuel usage found in the NAVSEA Shipboard Energy Conservation Guide. The resultant savings is shown below.

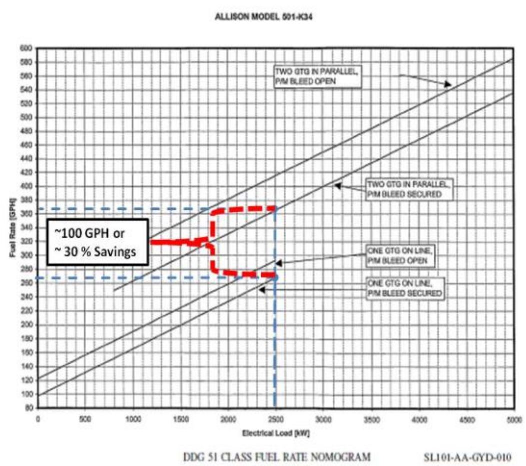


FIGURE 2. DDG 51 Fuel Usage Nomograph

Fuel Usage in GPH is plotted on the vertical axis vs. Electric Load in KW on the horizontal axis, with lines representing two generator and single generator operations. The resulting savings from this calculation is ~ 100 GPH at the load conditions specified above. This is consistent with but slightly higher than the results obtained using the 501-K34 SFC curves in Figure 1, and reinforces the concept that enabling single generator operations, while providing backup power to support the full ships electrical load in case of a GTG casualty would save a significant amount of fuel. Figure 3 graphically depicts the difference between the current practice of normal cruise with 2 Gensets, and Single Generator Operations “SGO”

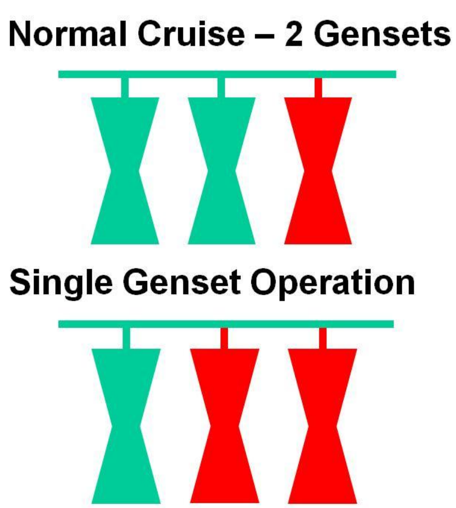


Figure 3 Single Generator Operations (SGO)

The fleet average DDG 51 underway fuel usage is on the order of 25.2 Bbls/Hr (average of 2010 PACFLT & LANTFLT DDG-51 Class fuel usage from Navy ENCON program). The electrical fuel usage for 2 generator operations at the load specified above is ~7.5 Bbls/Hr, or 30% of the total fuel usage and roughly 5.5 Bbls/hr for the single generator case. The resulting “electrical fuel savings” for this Single Genset with ESM mode of operation of ~2 Bbls/Hr translates to almost 30% savings of “electrical” fuel, and ~ 8% of overall ships underway fuel usage.

System and Technology Overview

The ESM Modules developed under the ONR Contract consist of a modular bi-directional AC/DC power conversion system. This is based on significant improvements to the RCT Systems PCM-2 Ship Service Inverter Modules (SSIMs) that were successfully tested as part of the NAVSEA DDG(X) Integrated Fight Through Power (IFTP) program to develop the power conversion components (AC/DC, DC/DC and DC/AC) that were the prototypes for the DDG-1000 Low Voltage Power Distribution System. The PCM-1 and PCM-2 Ship Service Converter Modules (SSCM) were thoroughly tested at NSWC Philadelphia Land Based Test Site (LBTS).

The ESM also includes the necessary controls, and system interface devices, along with modular Energy Storage (ES). The system interfaces with the Ships 450VAC distribution and includes a high voltage DC-link for connection with the battery or other ES. While the module size is notionally 600 kW (5 would support a 3 MW load), the system can be scaled to meet shipboard power and space needs concepts for DDG 51 or other ship classes where fuel efficiency and energy storage are requirements. The modular system is shown schematically in figure 4.

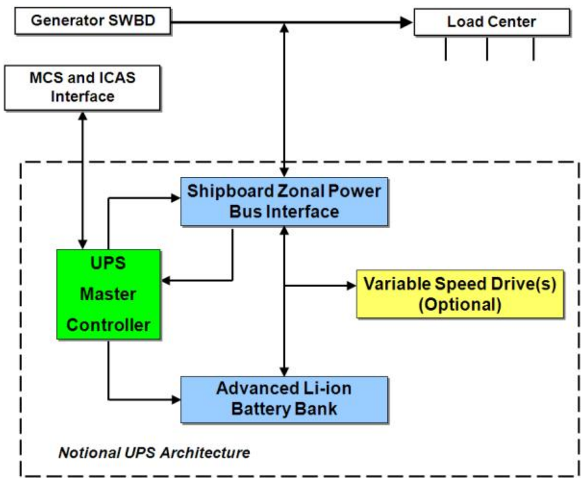


FIGURE 4. Notional DDG 51 ESM Module and Ship Interface.

The overall system objectives (figure 5) were derived from the estimated requirements to provide continuity of power for up to 10 minutes given the loss of a single generator. A distributed, modular and redundant system was developed based on the desire for a 3 MW system (current RR 501-K34 GTG). Each module is rated at 600 kW.

System Design Objectives

Outline including shock excursion	90" W x 81" H x 52" D
Maintenance space	24" on right side, 44" in front
Overall Weight	12,800 lbs (including "battery")
Empty Cabinet Weight	1,400 lbs.
Handling	Hatchable
Power Quality	MIL-STD-1399-300 Type I
Power Rating	600kW
Discharge time	~10min (goal)
Cooling	Sea water or fresh water 0 - 35°C, 20gpm
Hardware Configuration	TRL-6 with a design that allocates space for components and functionality for >TRL-6
EMI	MIL-STD-461

FIGURE 5. System Design Objectives

The development of multiple line replaceable units (LRUs) for the bi-directional AC/DC inverters led to a tested 200 kW/LRU design. This equates to power densities of 1.78 kW/liter respectively (up from 0.90 kW/liter for IFTP converters). For the purpose of the demo, the LRU's were rated at 150 kW, so the resulting "module" now consists of 4 – 150 kW LRUs, plus batteries for a notional module power rating of 600 kW. Once again, five (5) modules would be required for a full 3 MW system (at the 150 kW LRU rating or 4 modules at the full LRU rating of 200kW/LRU). An isometric of the LRU packaging is shown in Figure 6.

A weight estimate/budget for the system is shown in Figure 7. At present the module weight is estimated to be 9000 lbs, assuming a Li-ion battery system weight of 4000 lbs (based on the 10 minute storage requirement). Given the maximum weight for the purposes of ship structural considerations, that leaves a margin of 3800 lbs for growth for shock mounts, and other structural, or containment systems.

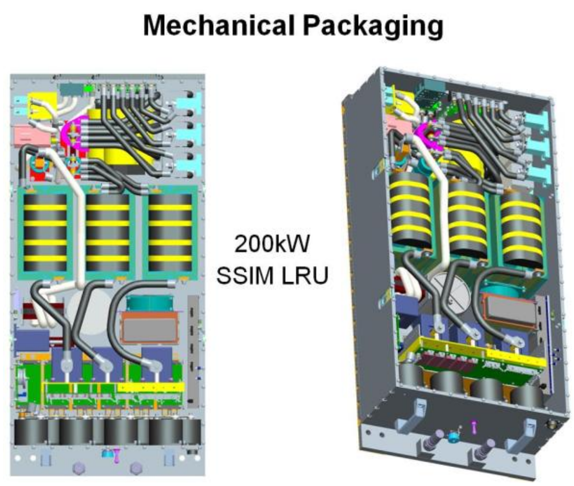


FIGURE 6. LRU Isometric

System Weight Estimate

Battery	4000 lb
Empty cabinets, 4 x 425 lb	1700 lb
SSIM LRUs, 4 x 400 lb	1600 lb
Bus Bars, Wires, Cable, Lugs, Term. Blocks	500 lb
Cooling system	400 lb
Mounting Brackets, angles, etc.	300 lb
BOP Misc.	200 lb
CPS	150 lb
Master Controller	80 lb
Diode OR-ing Assy.	70 lb
Total	9000 lb
Specification max.	12800 lb
Margin	3800 lb

Allows for growth due to fully shock compliant cabinet structure, etc.

FIGURE 7. 600kW Module Weight Estimate

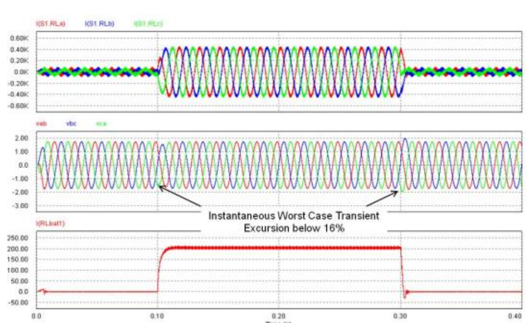
The complete ESM showing the open bay with the 4 LRUs is shown in Figure 8.

Figure 8. Modular ESM Cabinet with LRU's

In the system development all appropriate shipboard shock, electrical (MIL-STD-1399 Section 300 Type I power quality), EMI/EMC (MIL-STD-461) and related standards were incorporated into the design, but since this was a prototype development program, compliance testing was not done. A MIL-STD 882 Risk Analysis was conducted, and all potential mishaps have been addressed. System simulations were conducted to look at response to step load changes (e.g. loss or startup of a generator), short circuits, and autonomous paralleling of ESM modules with the generator.

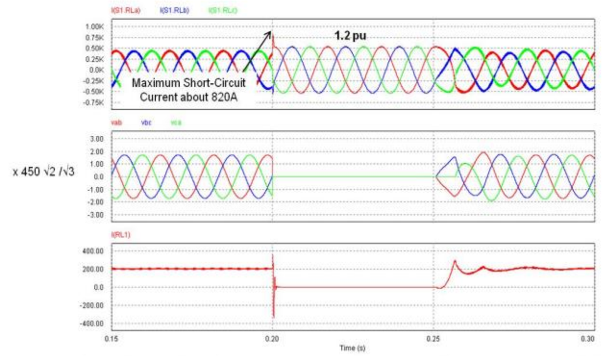
Representative simulation results are shown in figures 9 and 10 below.

SSIM Response to Load Steps (1)



100% (200kW 0.8pf) Load Acceptance at 0.1 Second
100% (200kW 0.8pf) Load Rejection at 0.3 Second

FIGURE 9. Response to 100% step load



3Φ Short Circuit Applied at t=0.2s and Removed at t=0.25s, 200kW, 0.8pf

FIGURE 10. Response to Short Circuit

Energy Storage Technologies

While the system is agnostic to the energy storage technology (battery, fuel cell, flywheel, etc.), the cabinets and system have been designed around advanced Lithium Ion battery technology. An energy storage specification was developed that detailed the "battery" performance criteria as shown in Figure 11.

Energy Storage Requirements

- **106 kW-hr Total Energy Capacity, 636kW** (accounts for Inverter efficiencies) for 10 Minutes
  - Over 360MJ stored energy available in each module
- **1000 VDC Maximum Voltage**
- **680 VDC Cut Off Voltage**
- **4 Separate Strings Preferred Configuration**
- **Built in Battery Management System (BMS)**
- **4000 lbs Maximum Weight, Excluding Cabinets**
- **Liquid cooling available**
- **NAVSEA INST 9310.1B and S9310-AQ-SAF-010 Compliant**
- **MIL-STD-882 Safety Program**

FIGURE 11. Energy Storage Requirements

Inputs were solicited from key battery suppliers who are involved with military battery development programs or who are currently providing batteries to the Navy. We confirmed that multiple vendors can meet the performance, size and weight of the battery system required to meet the original 10 minute duration.

System Manufacturing and Testing

A design review was held in early 2010 with the ONR sponsor, and manufacturing of the prototype 600kW module was completed and system testing conducted in December 2010 at RCT Systems in Linthicum, MD. A schematic of the test set up is shown in Figure 12, with a graphic of the test facility shown in Figure 13.

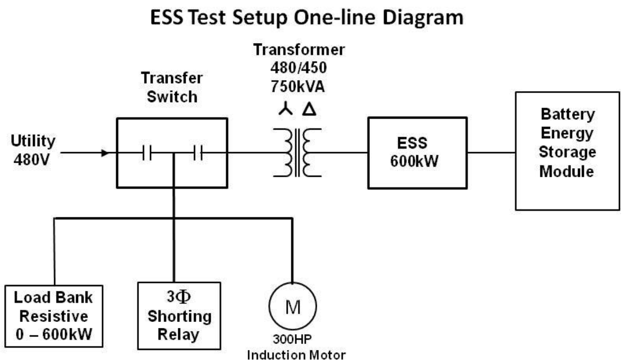


FIGURE 12. 600kW Module Test Diagram

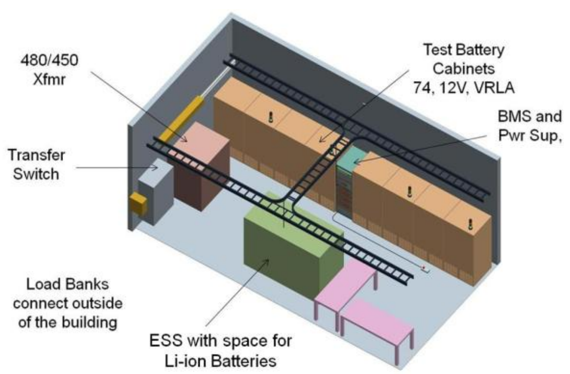


FIGURE 13. 600kW Module (ESM) facility

As mentioned above, while the 600 kW module in Figure 13 was sized to include Lithium ion storage batteries (636kW for 10 minutes) within the module cabinets the testing was conducted with Valve Regulated Lead Acid (VRLA) batteries as shown above.

Ship Considerations

During the proposal evaluation phase of the BAA, ONR tasked Bath Iron Works (BIW) to review proposal feasibility from a ship arrangements standpoint. Given that this is a distributed, modular system that ties in to the ships electrical distribution system and has no mechanical connections with the propulsion system, there is a great deal of flexibility on where the system can be located. BIW found several potential spaces for the 84” W by 71” H by 48” D 600kW hatchable modules (figure 14), mostly in Storerooms around the ship.

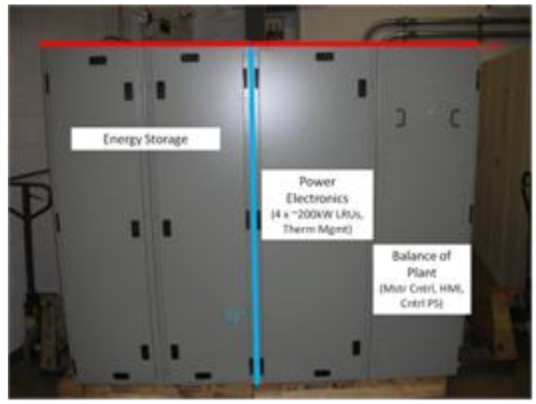


Figure 14. 600kW Module Cabinets

The bottom line is that multiple spaces exist for the installation of this system on DDG 51. Other larger ship classes would in general be easier to find spaces to back fit a system like this.

Other Benefits

In addition to the direct “electric plant” fuel savings, and reduced operating hours on the Gensets and consequently reduced maintenance burden, the addition of an energy storage system such as proposed here has other synergistic benefits, including:

Enables the adoption of advanced fuel efficient gas turbine generators

The current Rolls-Royce 501K34 is a single spool engine (compressor and power turbine are on the same shaft) which enables the generator to respond almost instantaneously to load changes. Twin-spool or “free power” turbine machines (compressor and power turbine are decoupled mechanically on separate coaxial shafts), such as the General Electric GE-38, or Rolls-Royce MT-7, with a power rating of ~ 4 MW would be more efficient than the current Gensets, providing additional fuel savings on the order of 15%. The challenge with this type of machine is that because of the mechanical decoupling, there is a delayed response to step changes in electrical load as shown in figure 15 that must be accommodated by some form of stored energy. For the purpose of discussion assume that the load on a twin-spool generator is 1.0 MW, and at time t=0 the generator sees a step load increase of 3 MW, up to a new load of 4.0 MW. Because the twin-spool machine cannot respond instantaneously, but rather follows a ramp up to the desired power level there is an energy deficit, in this case 4.5 MJ. One option would be to build sufficient energy storage into the generator subsystem, or as we propose have the distributed ESM provide for the energy deficit.

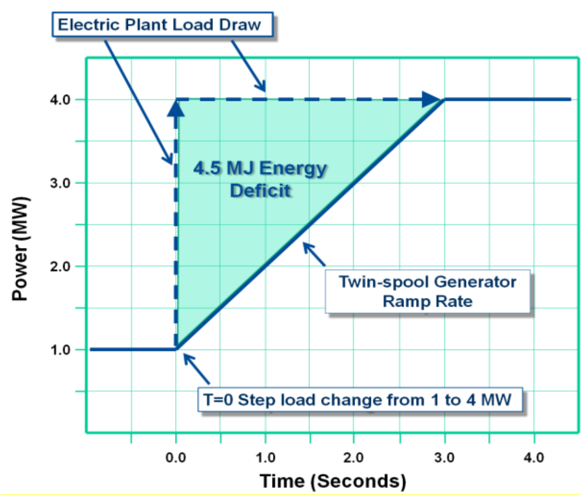


Figure 15. Energy Storage Needed for Step Load Change

The proposed ESM capacity of 1800 MJ (3 MW x 600 seconds) is 400 times what would be required by this hypothetical step changes (3 sec duration), and could easily provide the necessary energy demand if designed appropriately

Energy Storage: Future Sensors / Weapons

The power required for next generation Sensors and Weapons systems may rival propulsion power demands, and the transient pulsed loads will provide significant challenges to the architecture of future ships electrical distribution systems where energy storage modules will be essential. Such systems as the Advanced Missile Defense Radar (AMDR) for Ballistic Missile Defense; the Electromagnetic Rail Gun (EMRG) a revolutionary long-range naval gun that will fire precision-guided hypervelocity projectiles to ranges greater than 200 nautical miles; the Free Electron Lasers (FEL) which will provide a highly effective point defense capability against surface and air threats, future anti-ship cruise missiles or a swarm of small boats, utilizing an unlimited (electrical) magazine with speed-of light delivery, and others will all demand a significant Energy Storage capability which the ESM system can contribute to.

Relation to Navy Shipbuilding Plan

On March 28, 2012 DoD delivered the FY-13 version of the "30 Year Plan" to Congress, summarized in (Table 1).

Table 1. Near, Mid, and Far-Term Naval Battle Force Levels

	Near-Term 2013-2022	Mid-Term 2023-2032	Far-Term 2033-2042
Type	**FY 2017**	**FY 2028**	**FY 2040**
CVN	11	11	10
LSC	82	89	88
SSC	32	52	55
SSN	50	43	49
SSGN	4	-	-
SSBN	14	12	10
Amphib	30	34	31
CLF	29	29	29
Support	33	33	33
Total	**285**	**303**	**305**

Note: LSC – Large Surface Combatant
(CG 47, DDG 1000, DDG 51, CG(X) classes)
SSC – Small Surface Combatant
(LCS, FFG-7 classes)

Of the 82 Large Surface Combatants (LSC) planned in 2017, today the Navy has 22 CG 47 Class Cruisers and 61 DDG 51 Class Destroyers

(36 Flt IIA) in service, while several CG-47 Class Cruisers will be retired. The DDG 1000 and several DDG 51's are under construction, and the remaining 2 DDG 1000's have been awarded. The Navy plans to begin procuring a new version of the DDG-51 design, called the Flight III design, starting in FY2016. The bottom line is that in the near term (2017) DDG 51's will make up at least 75% of the LSCs, and that percentage will increase with retirement of older cruisers.

The Department of the Navy therefore can utilize spiral upgrades to existing ships to the maximum extent possible, and to extend the service lives of specific classes of ships. The opportunity to address fuel efficiency/cost issues, while incorporating Energy Storage to support advanced sensors and weapons systems can therefore be addressed during the "spiral upgrades" or service life extension of existing ships as well as the construction of new DDG's.

Testing

Factory testing at RCT Systems in Dec 2010 demonstrated Technology Readiness Level (TRL) 4+. The testing confirmed synchronization with utility power through a 440VAC/450VAC transformer, detection of loss of source waveform, and transfer of both resistive load bank and motor load from utility power source to VRLA fed ESM power source. Additionally, motor load fault response was demonstrated with a three phase bolted fault on the ESM fed bus while feeding resistive loads.

Following completion of the RCT led development and successful factory testing, the ESM, battery strings, and related hardware were transferred to NSWCCD for further development, land-based testing, and preparation for ship-board demonstration. To support the eventual ship-board demonstration installation, the delivered hardware was installed in a modified ISO container, the ESM Proof of Concept (PoC) Demonstrator, to facilitate simple installation and removal from the selected demonstration vessel helicopter hanger. The ESM PoC Demonstrator was installed at NSWCCD-SSES with access to both utility power source and the DDG51 Land Based Engineering Site (LBES) electrical plant. In general, land-based testing at NSWCCD-SSES will duplicate factory testing to verify proper ESM system reconstruction, verification of ESM firmware to synchronize with a gas-turbine generator (GTG) fed electrical plant bus waveform, detect loss of bus waveform, and supply bus load. GTG integration testing will characterize ESM behavior to resistive and inductive loads, motor loads up to 120hp, motor starts on ESM up to 120hp, and automated bus transfer switch behavior during GTG to ESM transitions. LBES testing will provide a rigorous characterization of the ESM PoC Demonstrator over a broad range of scenarios and transients that may occur onboard ship. Successful completion of these tests will provide a quantitative measure of system robustness with respect to programmed performance and operation.

Subsequent ESM PoC Demonstrator shipboard testing will cover a subset of this testing with exception that real shipboard loads will be used instead of load banks and motors. The ESM PoC Demonstrator will be tied into multiple breakers on a load center. The electrical plant will be aligned such that a generator, generator switchboard, and main switchboard fed load center feeding loads and the ESM PoC Demonstrator will be islanded from the rest of the electrical plant such that ~460kW of load is available for demonstration testing. Demonstration testing will highlight ESM synchronization, load transfer, and GTG paralleling to re-accept load. It is also anticipated that long term paralleling (with no discharges) will be demonstrated on the ship.

Future Development

During 2011 and early 2012, the Electric Ships Office (PEO SHIPS PMS 320) implemented a plan to develop requirements for an ESM system suitable for backfit on DDG 51 Class Flights I and II ships. The system will facilitate fuel savings by derisking single generator operations on these ships as discussed in the Introduction section above. To determine appropriate requirements, lessons learned from the ONR program, including the NSWCCD Philadelphia testing, were heavily leveraged. In addition, studies were conducted to collect data and develop appropriate overall power/energy requirements such that the resulting system will provide enough energy to prevent dark ship conditions without being oversized, thereby taking up more space and being heavier than necessary. The resulting specification is currently in the review and approval process at NAVSEA. NAVSEA issued the specification as a draft for industry comment on May 4, 2012 to ensure the requirements are achievable.

In parallel with this effort, a Draft Request for Proposal is being prepared for release, to be followed by a formal Request for Proposal, to design and build Energy Storage Modules to support qualification and integration testing at NSWC-CD SSES Philadelphia, as well as environmental qualification testing. Upon successful qualification, it is anticipated that production to support DDG 51 ship installations will soon follow.

CONCLUSIONS

While the development of this modular Energy Storage System (ESM) was targeted to the DDG 51 Class as a fuel efficiency improvement, the technology has wider applicability to other ship classes for energy storage (UPS) needs, energy efficiency improvements, and as an enabler for the NGIPS architecture and future weapons and sensor systems. The distributed, modular, hatchable system can go anywhere on the ship where space is available since it needs no special support other than salt water cooling.

The completion of testing to TRL 4+ of the prototype DDG 51 ESM in December 2010 provided the initial demonstration of an advanced shipboard energy storage system, that will enable significant fuel savings for the DDG 51 Class, as well as other current and future ship classes. Testing leading to TRL 5+ at NSWC-CD Philadelphia at the DDG 51 Land Based Engineering Site (LBES), will be completed in 2012 and eventual at sea testing in a DDG 51 Class ship is planned for late summer/fall of 2012. Competitive procurement of an ESM can support DDG-51 Class backfit installations starting in 2016.

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US Navy Incentivized Energy Conservation (I-ENCON) Quarterly Reports (NAVSEA 05Z1)

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John Heinzel *is a senior chemical engineer working in the Energy Conversion Research and Development Branch of NSWCCD-Philadelphia. John has significant experience in the development, modeling and evaluation of chemical and electrochemical systems, as well as system design and integration with respect to shipboard requirements. This range of knowledge and experience has allowed him to take on key roles in the design, fabrication and test of advanced energy conversion systems for use in a variety of Navy applications. John's key areas of research and oversight include Energy Storage and Advanced Power Generation for application in Navy environments. He has held key roles in a variety of programs including serving as Program Manager for both the 600kW Altairnano Lithium Titanate Battery Development, and the 600kW Shipwide UPS Development Swampworks Program, and is currently serving as Navy Lead under the OSD/ARPA-E Hybrid Energy Storage Module developmental program. He is also the Battery IPT and Energy Storage Development and Qualification Lead for the Electromagnetic Railgun Innovative Naval Prototype and transition, amongst efforts on other active programs. He spans execution support across ONR and NAVSEA, and is actively engaged in transition processes. He received his B.S. in Chemical Engineering from the University of Delaware in 2002, and his M.S. in same from Rowan University in 2004. John is also currently pursuing his Ph.D in Chemical Engineering from Auburn University, focusing upon interactions of organically bound sulfur with metal and metal-oxide surfaces, and harnessing these interactions in useful architectures, pertinent to shipboard process equipment.*