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Hydrodynamic Energy Saving Enhancements for DDG 51 Class Ships

ABSTRACT

In February 2011, the U.S. Navy accepted it's 60th DDG 51 Class destroyer, and there are still many more to be built. Propulsion fuel efficiency on this class thus becomes a fertile area for cost saving. NSWCCD has recently embarked on the design of an initial Stern End Bulb for potential retrofit on the DDG 51. Powering evaluation via computational fluid dynamics methods and scale model testing has been completed for an initial stern end bulb design. The speed improvement and the potential fuel saving is presented. In addition, updated fuel savings potential associated with many previously proposed hydrodynamic improvements such as the DDG 51 retrofit bow bulb, a larger diameter propeller, propeller pitch sensor and setting of optimal pitch, stern flap design, twisted rudder, and hull and propeller cleaning, are discussed and fuel savings are estimated.

INTRODUCTION

The USS ARLEIGH BURKE (DDG 51) Class destroyer represents the latest in a distinguished lineage of combatants designed and developed by the U.S. Navy. It is one of the world's finest military hullforms, optimizing speed, power, seakeeping, stability, and payload capacity, even though its initial design dates back nearly three decades. Since the first-of-class DDG 51 became operational in 1991, the hydrodynamic community has unveiled numerous advances in ship technology and design.

Many advances in ship technology were developed for the DDG 51 at the Naval Surface Warfare Center Carderock Division (NSWCCD), by the Hydromechanics Directorate (Code 50), Cusanelli et al. [Ref. 1]. Model scale experimentation in the celebrated David Taylor Model Basin (DTMB) and the unique Large Cavitation Channel (LCC), were utilized in conjunction with advanced computational fluid dynamics (CFD) techniques for the development of these technologies. In addition, ship trials have been conducted on several prototypes in order to demonstrate full-scale performance improvements.

These technological improvements were developed to enhance the operational performance of combatants, or to foster reductions in operating and life cycle total ownership costs (TOC), or a combination of both pursuits. All of the developed technologies have the potential for transfer to future combatant designs. Several of these technologies are mature, and have either been implemented within the fleet or are ready to be implemented. Other presented technologies would clearly require additional R&D.

The following technologies will be reviewed. The focus will be on the potential for annual fuel savings.

- 18ft Diameter Propeller: Increased diameter to increase propeller efficiency.
- Contra-Rotation Propellers: To increase propeller efficiency.
- Retrofit Bow Bulb: To reduce fuel consumption.
- Stern End Bulb: To reduce fuel consumption.
- Accurate Pitch Measurement: For improved pitch-scheduling ability to reduce fuel consumption.
- Updated Stern Flap: To reduce fuel consumption.
- Twisted Rudder: To lessen cavitation erosion damage to reduce maintenance costs.
- Hull and Propeller Cleaning: To prevent increase in power and loss of propeller efficiency.

Data from the FY12 Navy Energy Usage Reporting System[1] (NEURS) indicates that the DDG 51 Class average annual total underway fuel usage is 76,269 bbls/yr/ship, and the average annual propulsion fuel consumption is 56,420 bbls/yr/ship. Thus, a technology that results in just a 1 percent propulsion fuel savings (564 bbls) would yield an annual fuel cost savings of nearly $100K per ship, using the standard fuel price of $175/bbl established for FY12.

The original and subsequent powering performances and associated fuel savings of all the technologies presented in this paper were determined by a wide

[1] FY12 NEURS Baseline Fuel Rates (derived from NEURS data of FY08-10: 3-year class average) combined LANT and PAC fleets.

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assortment of methods employed at the time of the evaluations. During the preparation of this document, the authors undertook the task of re-evaluating the performances of all of these energy technologies by the current FY12 fuel calculation method, as outlined in the Appendix. All fuel savings presented herein are adjusted to reflect the current FY12 calculation method, the FY12 NEURS Class average propulsion fuel consumption, and the standard fuel price of $175/bbl established for FY12.

18ft DIAMETER PROPELLER

Recently, the possibility of a new 18 ft (5.5 m) diameter controllable-reversible pitch (CRP) propeller design has been proposed as an efficiency improvement for the next flight of DDG 51 class ships. A study was prepared of the costs, time and benefits of implementing a new 18 ft propeller on the existing DDG 51 propeller hub for new construction as well as for retrofit on existing hulls.[2]

In the early 1980s, during the initial design spiral of the DDG 51 Class, both 17 ft diameter and larger 18 ft diameter CRP and fixed pitch (FP) propeller designs were considered. Through model propeller open water testing and powering performance, the 18 ft CRP design was demonstrated to be more efficient than the 17 ft CRP design. However, at that time, the 17 ft design was selected due to perceived geometric and loading capacity restrictions on the existing CRP propeller hub design. A significant investment would still be required to redesign the current 17 ft CRP hub to convert it to an 18 ft diameter propeller.

The previous 18 ft design was optimized for operation at the ship's full power speed. Due to this design criterion, when the ship is running at speeds less than 25 knots this propeller is less efficient than at full power. Because the DDG 51 Class spends a great majority of the time operating at low speeds, only about 14% of the fuel usage for propulsion per year is used at speeds greater than 25 knots. Therefore, if a propeller change is made to improve efficiency, the new 18 ft propeller design will have to be more efficient, below 25 knots, than the previous design.

To estimate the performance of a new 18 ft diameter propeller design, optimized for cruise speed, the open water efficiency of the fleet 17 ft propeller was scaled by the increase in ideal efficiency of an 18 ft versus 17 ft propeller. The ideal efficiency is increased with the larger diameter because the thrust coefficient is decreased. This resulted in the 17 ft propeller open water efficiency being scaled by 1.4% to account for the increase in diameter, Fig. 1. The new delivered efficiency (eta_D) was calculated using the interaction coefficients from the 18 ft propeller powering test and the scaled open water efficiency curve. The estimated increase in eta_D between the 18 ft versus the 17 ft diameter propellers was in the range of 0 to 3.5 percent over the DDG 51 speed range, Fig. 1.

Summarizing the effects of the increased propeller efficiency, using the DDG 51 Class current FY12 fuel calculation method, an annual fuel reduction of 439 bbls/year per ship (0.8%) is projected for a new 18 ft diameter propeller, corresponding to a fuel cost savings of $77K annually per ship.

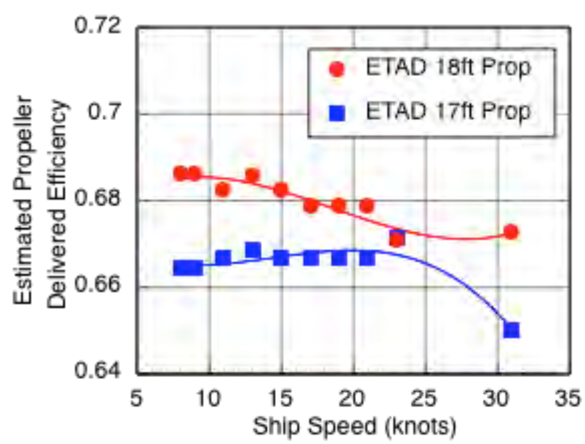

Fig. 1. Estimated DDG 51 propeller delivered efficiencies, 18 ft versus 17 ft diameters

A new 18 ft diameter DDG 51 propeller design would employ all of the technology advancements of the New Blade Section Propeller, an alternative CRP propeller designed part way through the procurement of the DDG 51 Class, Bailar et al. [Ref. 2]. Model tests of the new blade section propeller verified an improvement in propeller cavitation over the original propeller with standard blade sections, Jessup et al. [Ref. 3]. The new propeller was selected to replace the existing fleet propeller for the DDG 79 Class (Flight IIA).

The new blade section propeller was installed on USS BARRY (DDG 52), and evaluated, Hundley et al.[3]

[2] M. Brown and S. Black, "Business Case for DDG-51 Class Propeller Redesign", NSWCCD Code 5800, 11/3/10.

[3] NSWCCD Code 50 report of limited distribution.

Full-scale improvements in cavitation were similar to those exhibited at model-scale. After 2 years of operation, the new propeller was inspected and was found to be free of any erosion damage. This is in contrast to the original fleet propeller, which, after 2-3 years of service, has shown significant erosion pitting and localized bending of the trailing edges due to extensive sheet cavitation at full power conditions.

CONTRA-ROTATION PROPELLERS

A conventional single propeller causes a significant amount of rotational flow, the energy of which is mostly lost as it flows downstream. To utilize this wasted energy, a second propeller is placed behind the first, rotating in the opposite direction, referred to as a contra-rotating (CR) propeller pair. If ideally designed, a CR propeller pair will have no rotational flow aft of the second propeller disk, resulting in low induced energy loss and high efficiency.

An investigation of CR propellers on DDG 51 utilized the customary application, where the propulsion power to drive the CR propeller pair was applied down a single coaxial shaftline (in this case, a pair of coaxial shaftlines driving two sets of CR propellers). For simplification, the diameters of the strut barrels and bossings, and size of the shaftline support struts, were assumed to be the same as that of the present fleet CRP propulsion. This was justifiable as a first approximation, however, if a CR propulsion system was to be installed, the shafts, struts, barrels, etc., would have to be sized correctly, and the effect on powering would have to be further investigated. In addition, further R&D would be required for the design of the complex mechanical coaxial shaftline drive system, gear sets, bearings, seals, etc.

Two different contra-rotating (CR) propeller designs were developed. CR propeller design #1 (CR-1) was optimized for propulsive efficiency, while maintaining the cavitation performance of the fleet propeller. CR propeller design #2 (CR-2) was designed to minimize cavitation and to achieve an increase in cavitation inception speed, while maintaining the propulsive efficiency of the fleet propeller. Model-scale powering experiments were conducted in the linear towing basins, Cusanelli[4], and cavitation experiments were conducted in the LCC, Smith and Remmers[5], on both CR designs, and were compared to the fleet controllable-reversible pitch (CRP) propeller design.

Both the powering and cavitation experiments were conducted on models that were substantially larger than normal. Two 'sister' models of 36.2 ft (11 m) waterline length with a scale factor (λ) of 12.866 were constructed for use simultaneously in the DTMB linear towing carriages and at the LCC. CR model propeller diameters were equivalently large, 16.8 inch (42.7 cm) forward and 14.3 inch (36.3 cm) aft, Fig. 2.

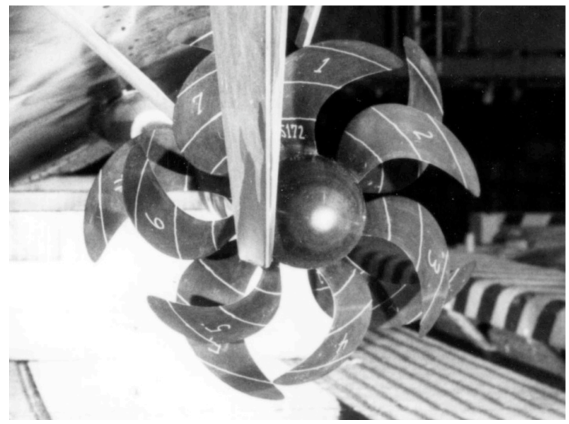

Fig. 2. DDG 51 CR-1 design model propellers

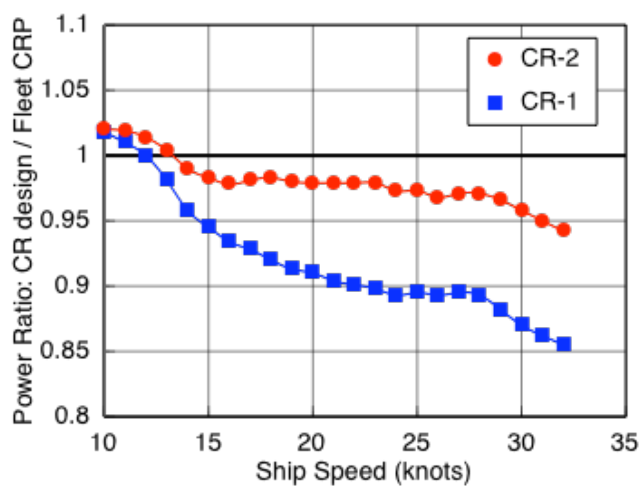

Fig. 3. DDG 51 contra-rotating propeller designs model-scale powering performance

The results of the model-scale powering tests, Fig. 3, indicated that the most efficient propeller design, CR-1, reduced the delivered power relative to the fleet CRP propeller by an average of 8 percent over the speed range, and had a peak reduction of over 14 percent. Again utilizing the DDG 51 Class current FY12 fuel calculation method, the CR-1 design was

[4] NSWCCD Code 50 report of limited distribution.
[5] NSWCCD Code 50 report of limited distribution.

projected to reduce the annual fuel consumption by 1532 bbls/yr (2.7%), with a consequential fuel cost savings of $268K. Similarly, model tests for CR-2 propellers, designed for cavitaion inception rather than efficiency, nonetheless indicated average and peak power reductions of 2 and 6 percent, respectively, a reduction in annual fuel consumption of 366 bbls/yr (0.6%), with a consequential fuel cost savings of $64K, relative to the fleet CRP propellers.

Cavitation experiments at the LCC showed that CR-2 had a significantly higher cavitation-free speed than the fleet CRP design, while CR-1 had a somewhat lower cavitation-free speed. CR-2 also showed significantly reduced thrust-breakdown at full power relative to the fleet propeller.

RETROFIT BOW BULB

A near-surface, small volume, hydrodynamic bow bulb, for use on U.S. Navy Combatants, has been developed and patented, Cusanelli et al. [Refs. 4, 5]. This new type of bulb, referred to herein as the Retrofit Bow Bulb, was integrated into the existing combatant bow which houses a sonar dome.

Sonar domes have been fitted to the bows of combatants principally to house the sonar transducers. They are generally located below the baseline of the ship, and can affect the ship resistance either positively or negatively, depending on speed. Bow bulbs are designed to reduce the ship's wavemaking resistance, and are generally placed (or extend) well above the baseline of the ship. Principal geometric differences between the sonar dome and the Retrofit Bow Bulb are depicted in Fig. 4. The bulb is located near the free surface waterline, is nabla shaped (inverted tear drop), and is of a reduced size, volume, and beam-to-height ratio, relative to the geometry of the sonar dome located beneath it.

The initial design and optimization of the bow bulb concentrated on calm water effective power reduction, which was demonstrated through model experiments. However, the design of a bow bulb with regard to only calm water performance can result in unfavorable performance in rough water, where the body of the bulb is subjected to an alternating inflow.

Further Retrofit Bow Bulb design refinement endeavored to retain the calm water resistance reduction through rough water. Three rough-water revisions of the bow bulb were model tested. All bulbs retained the equivalent bulb volume and longitudinal positioning, but were different in cross-section shape, Fig. 5.

Fig. 4. Retrofit bow bulb on DDG 51 model

Fig. 5. Cross-section shapes of candidate bow bulbs

Fillets were also developed for the upper and lower bulb intersections with the bow stem, which can be seen installed on the model in Fig. 4. The fillets smoothed the flow around the bulb and hull intersections, improved the bulb's low speed performance, and reduced the free surface disturbances during pitching motions in rough water.

The bulbs were evaluated at various vertical positions, in calm water, in sea state 4 (SS4) head and following seas, and in sea state 2 (SS2) head seas, Cusanelli [Ref. 6]. Combining calm and rough water data, summarized using the speed-time operational profile in use at that time, the bulb design with the greatest potential for life cycle fuel savings was selected as the Retrofit Bow Bulb. The selected cross-section geometry was the center bulb depicted in Fig. 5. This bulb had a substantial effective power performance improvement compared to the baseline (no bulb), in calm water and rough water (SS2 and SS4), throughout most of the speed range, Fig. 6.

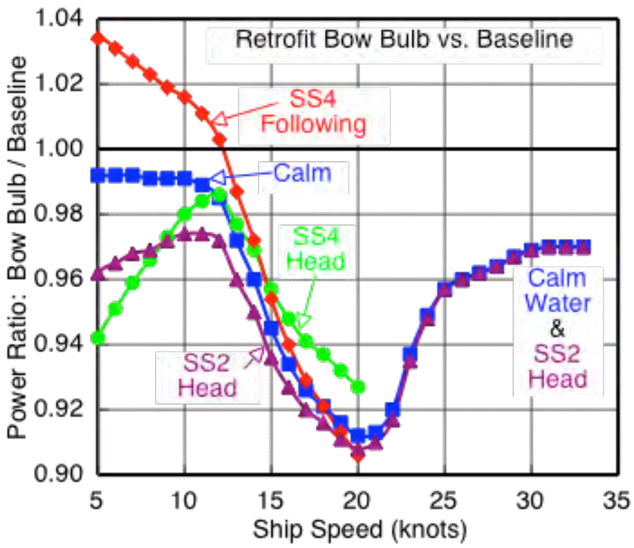

Fig. 6. Retrofit Bow Bulb model-scale performance in calm and rough water

Utilizing the DDG 51 Class current FY12 fuel calculation method, for strictly the calm water data, indicates an annual fuel reduction for the Retrofit Bow Bulb of 1469 bbls/yr (2.6%).

A method was developed to evaluate the annual fuel reduction for the Retrofit Bow Bulb in calm and rough water combined. Annual sea state occurrences for the open ocean northern hemisphere were utilized, as presented by Lee and Bales [Ref. 7]. The analysis utilized bow bulb projected performance averaged model-scale data from calm water and added powering in SS2 for calm water through SS3 analysis, indicated as occurring 27.2 percent of the time in the northern hemisphere. Model-scale data for added powering in SS4 was used for SS4 and above, indicated as occurring 72.8 percent of the time. The division of data for the propulsion fuel calculation assumed no ship operations above 20 knots in SS4 or above.

DDG 51 Retrofit Bow Bulb speed-time annual underway propulsion fuel calculation by the current FY12 fuel calculation method, with division by annual sea state occurrences, indicates an annual fuel reduction of 1334 bbls/year (2.4%), with a consequential fuel cost savings of $233K. The rough water inclusion results in little variation from the calm water analysis, due to the design criterion that the bulb performance vary little in SS4 relative to calm water.

The FY97 S&T Retrofit Bow Bulb Program also included tasks in the following areas:

• CFD was used to modify 'nose' shape for reduced pressure gradients, and to predict pressure fields and streamlines over bulb and sonar dome.
• Seakeeping and slamming model tests were conducted to determine effects of bow bulb.
• Wave induced loads tests on the bulb were conducted in SS3, 6, 7, and worst-case sea spectra (derived from hurricane Camille).
• Initial assessment was made of bulb influence on hull girder vertical loads.
• Dockside acoustic transfer function tests were made full-scale on baseline hull.
• Initial acoustic design guidance was addressed.
• Initial assessment was made of bulb construction methods, materials, and mounting issues.
• Anchor handling and mooring issues were assessed.

The FY97 S&T Retrofit Bow Bulb installation was cancelled due to the need for the relocation of the port side auxiliary anchor, rendering the effort economically unattractive. Since then, existing DDGs have removed this anchor, and it has not been installed on new DDGs. From an economic view, a previous major risk factor is no longer applicable.

STERN END BULB

It is acknowledged that a ship moving in the water generally creates a much larger bow wave than a stern wave. Thus, the most logical location for a bulb is at the bow because the large energy content in the bow wave is a potential source of more recoverable energy. Nevertheless, the stern end of the ship also generates waves that are a source of 'wasted' energy. In contrast to the plethora of technical reports on bow bulb design, and their universal and wide-spread usage at sea, there are only a few dozen technical reports and rare full-scale applications of stern end bulbs (SEB).

An Independent Applied Research (IAR) program was undertaken at NSWCCD with the intent of providing some guidance as to the resistance reduction possible for SEBs on combatants and auxiliaries, Karafiath [Ref. 8]. An initial DDG 51 SEB was designed and optimized by CFD calculations, using the Ship Wave Inviscid Flow Theory (SWIFT) potential flow computer code and the FreeRans viscous flow free surface computer code. Based on this CFD-optimized SEB, several variants were developed and manufactured for a Phase I series of model-scale tests. The Phase I SEBs were model-scale tested separately, and in conjunction with a modified stern flap, Fig. 7.

Fig. 7. DDG 51 Phase I Stern end bulb with stern flap installed on model

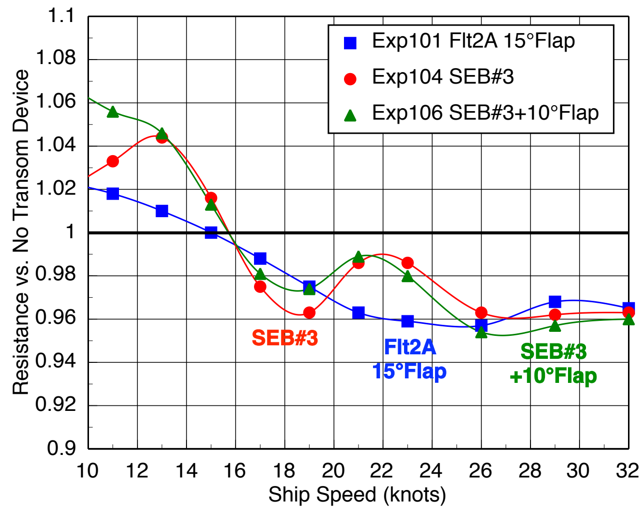

Fig. 8. DDG 51 Phase I stern end bulb and stern flap model-scale performances

The design challenge of a SEB on the DDG 51 is to overcome the already enhanced performance with the existing Flight IIA 15° stern flap. The best performing of the Phase I SEBs (designated SEB#3), although impressive by itself, was not able to improve upon the performance of the ship with the existing stern flap. However, above 26 knots, SEB#3 plus a 10° stern flap did perform better than the Flight IIA 15° stern flap, Fig. 8. All configurations of SEBs exhibited a low speed resistance penalty. Since the SEB performance is derived through potential flow wave making phenomena, there is no technical reason to assume that there is a beneficial scale effect to be applied to the low speed data, such as is done for a stern flap.

The Phase I model test results led to the development of several Phase II SEBs, the goal of which was the integrated with the stern flap, in order to foster better fuel saving performance than just the flap alone. For Phase II, eight different integrated SEB-flap designs were developed and evaluated through CFD.

Two of the most promising of the Phase II integrated SEB-flap designs were built and model tested. During the model-scale tests, none of the integrated SEB-flap designs were able to reduce the resistance below that of the existing Flight IIA 15° stern flap. However, careful examination of photographs comparing the stern wave systems developed behind the flap, SEB, and SEB plus flap configurations, revealed some possible areas for design improvement.

Phase III SEB designs will strive to improve the performance of the SEB and stern flap combination. CFD and model tests will be conducted to investigate the following design changes, as illustrated in Fig. 9.

- Modified SEB afterbody shape to include a 'cut-off' transom stern design, in order to avoid separation off the previous 'boat-tail' design.
- Modified SEB forebody 'nose' shape for modified pressure drag and reduced resistance.
- Variations in SEB volume and length.
- Variations in stern flap chord length, area, and angle.

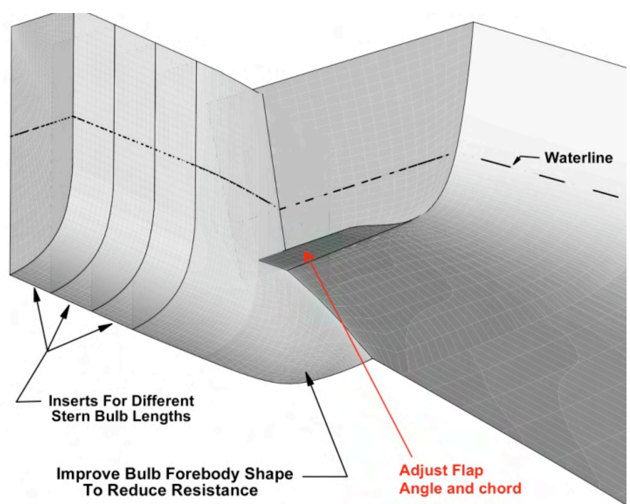

Fig. 9. Stern end bulb Phase III design iterations

ACCURATE PITCH MEASUREMENT

Implementation of a revised Program Control Module (PCM Version 6.0) has already commenced on DDG Flight IIA. PCM v6.0 provides the capability to switch between baseline control mode and a new fuel-efficient mode (FEM) that utilizes propeller pitch schedules developed for minimizing fuel consumption in full plant, split plant, and trail-shaft modes. Based on trials data presented by Hill[6], FEM offers fuel savings of about 4.0%, corresponding to $395K annual fuel savings per ship.

However, the ability of the FEM pitch algorithms to provide optimal settings for fuel efficiency, or to function at all, depends on the capability of the ship's monitoring systems to determine accurately the pitch of each propeller blade. That translates into accurately measuring the rotational positioning on the hub of each of ten propeller blades (five blades on each port and starboard propeller), continuously, while underway, at speed, and under all loading scenarios.

Propeller pitch can vary due to many parameters such as blade forces, propeller rotational speed, temperature and pressure in the hydraulic pitch control system, expansion and contraction of the pitch control rods, improper pitch calibration procedure, outdated pitch calibration, etc. Experience during hot pitch calibration procedures conducted by NSWCCD prior to powering trials has indicated that design (100%) propeller pitch as registered by the ship's systems is frequently in error by 2 to 5 percent, and in worst case situations has been in error by as much as 11 percent. A 5 percent offset in propeller pitch can reduce the propeller performance by an average of 1 percent near the design point, resulting in increased fuel consumption. In order to realize the potential fuel savings of the FEM, the propeller blade pitch must be measured and known accurately.

Previous mechanical type propeller pitch sensors have been installed in the interior of the propeller hub. The reliability and long term viability of these systems has been poor. The U.S. Navy will attempt to undertake the development of a direct propeller blade pitch sensor system that provides accurate pitch data, in water, while the ship is operational and underway at speed. Technologies such as direct in water distance measurement with a laser or an acoustic measurement system will be evaluated.

[6] NSWCCD Code 50 report of limited distribution

UPDATED STERN FLAP

A stern flap is an extension of the hull bottom surface created by a relatively small appendage welded to the transom of the ship. Stern flaps have now been deployed at sea since 1989, on a variety of U.S. Navy (USN) and U.S. Coast Guard (USCG) classes. Stern flaps have been proven during sea trials to reduce propulsive power, and to foster significant fuel cost savings, while increasing both ship range (endurance) and top speed, Cusanelli [Ref. 9].

The various stern configurations of the DDG 51 Class must first be thoroughly explained. In addition, the difference between stern flaps and transom wedges must be understood. Flaps and wedges are very similar, and also operate along similar principles, Karafiath et al. [Ref. 10]. While a stern flap is an extension of the hull bottom surface that extends aft of the transom, a transom wedge is located under and forward of the transom (and is generally inlayed into the hull plating).

The design of the original ARLEIGH BURKE (DDG 51), Flight I/II (DDG 51-78) hull, was completed in 1984. This hull included a 13-degree, 3.2 ft (1 m) chord length transom wedge inlayed into the hull plating. The current FY12 fuel calculation method utilizing the model-scale data indicated that the Flight I/II wedge produced a 0.8 percent reduction in annual fuel consumption, corresponding to $77K in fuel savings. At that time, the combatant stern flap had not yet been developed.

The design of the OSCAR AUSTIN (DDG 79) Flight IIA Class, which included a 5 ft (1.5 m) transom extension, was undertaken in 1989. In the interval, stern flaps had been proven successful on combatant hulls. A 15-degree, 3.2 ft (1 m) chord, 23.6 ft (7.2 m) span stern flap was shown to have the best potential for fuel reduction and increased top speed, Forgach.[7] The current FY12 fuel calculation method utilizing the model-scale data indicated that the Flight IIA stern flap reduced the annual fuel consumption by 2530 barrels (4.5%), corresponding to a fuel cost savings of $443K per ship. The stern flap was installed as a new construction item on OSCAR AUSTIN (DDG 79), Fig. 10, and is to be installed on all subsequent Flight IIA hulls, of which 34 hulls are currently active (DDG 79-112), and which will eventually number 44 in total (through DDG 122).

[7] NSWCCD Code 50 report of limited distribution.

Fig. 10. DDG 79 Flight IIA stern flap on OSCAR AUSTIN (DDG 79)

A stern flap, which could be retrofit behind the transom wedge, was successfully developed in 1996 for the original DDG 51 Flight I/II hull. Model tests indicated that the stern flap could reduce the power and fuel requirements over the wedge alone, Cusanelli et al. [Refs. 11, 12]. The Flight I/II retrofit stern flap was 13-degrees, chord length of 4.7 ft (1.4 m), and span of 24 ft (7.3 m). The initial installation of the Flight I/II retrofit stern flap was on the CURTIS WILBUR (DDG 54) in Feb, 2000, Fig. 11. It has subsequently been installed on all 28 Flight I/II hulls (DDG 51-78).

Fig. 11. DDG 51 Flight I/II retrofit stern flap on CURTIS WILBUR (DDG 54)

The Flight I/II retrofit stern flap was installed on RAMAGE (DDG 61), in 2000. A full-scale stern flap evaluation program was conducted on RAMAGE, consisting of a Baseline (pre-flap) Trial and a subsequent Stern Flap Trial. The flap was installed on RAMAGE while afloat, at pier-side, via a cofferdam, thus avoiding a lengthy drydock availability and significantly reducing the time period between trials.

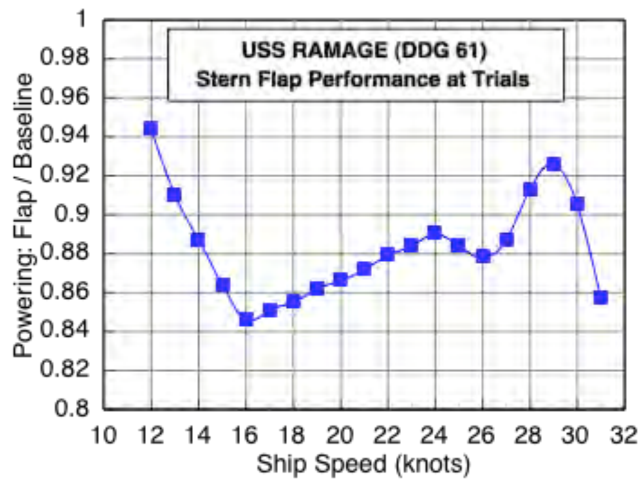

Fig. 12. DDG 51 Flight I/II retrofit stern flap full-scale trial performance on RAMAGE (DDG 61)

The trials results on RAMAGE indicated that the flap reduced delivered power by 5-15%, Fig. 12, and increased the ship's top speed by 0.9 knots, Cusanelli et al.[8] A propeller pitch adjustment was required to obtain the full benefits of the flap performance at high power, and necessitated a subsequent modification in the Flight I/II Program Control Module. Utilizing the DDG 51 Class current FY12 fuel calculation method, the reduction in annual fuel consumption determined from the trials is 3002 bbls/yr (5.3%), corresponding to a fuel cost savings of $525K per ship.

The current extended build schedule of the DDG 51 Class includes the possibility of 24 additional ships of a Flight III design (DDG 123-146). The Flight III will have a significant increase in ship displacement and a corresponding increase in draft, and the possibility of another elongation of the hull. These ship modifications, in combination with the likelihood of updated or altered mission and speed-time profiles, would indicate that a re-evaluation of the existing Flight IIA stern flap design is in order for Flight III.

A possible model-scale R&D evaluation of the usage of interceptors in conjunction with a stern flap design has also been contemplated for the Flight III. The interceptors, which can be deployed or retracted as

[8] NSWCCD Code 50 report of limited distribution.

desired, could be located at either the flap leading edge (transom knuckle) or at the flap trailing edge.

It has been determined at NSWCCD that the use of a substantially large model is required for the accurate determination of performance of these types of transom appendage configurations. Model-scale stern flap experiments were conducted on three different DDG 51 Class geosim models, a large 38 ft (11.6 m) scale ratio 12.866 model, a mid-size 24 ft (7.3 m) scale ratio 20.2609 model, and a small 14 ft (4.3 m) scale ratio of 36.0 model, Cusanelli [Ref. 13]. The stern flap performance improved as model size was increased. Qualitative observations and resistance measurements indicated that the 14 ft (4.3 m) model was too small for an accurate prediction of stern flap performance. The model tests also indicated that this model was too small to develop accurate transom flow patterns or transom flow detachment.

The stern flap performance exhibited at each of the three model scales was then compared to the full-scale stern flap performance on RAMAGE. Through these model experiments, associated CFD calculations, and full-scale performance comparisons, stern flap scaling effects were firmly established, Ref. 13. A NSWCCD proprietary analysis tool for scaling stern flap model-scale experimental results to project full-scale stern flap performance was formulated.

TWISTED RUDDER

Rudder cavitation has become a maintenance issue on the DDG 51 Class. Drydock inspections have shown severe erosion damage on the rudder, Fig. 13. Photo-viewing trials showed surface cavitation occurring on the rudder in the same area. Periodic repair of the eroded rudders increases the maintenance cost and decreases ship operation time.

Although it is common practice to place the rudders in the propeller slipstream to take advantage of the accelerated flow for enhancing the rudder side force, it can cause problems from cross-flow velocity components in the propeller wake. Consequently, a project was initiated by the U.S. Navy to develop computational capabilities to predict propeller-rudder interaction and to develop a new rudder design method to improve cavitation performance. This new method was used to design a new 'twisted' rudder for the DDG 51, Shen et al. [Ref. 14].

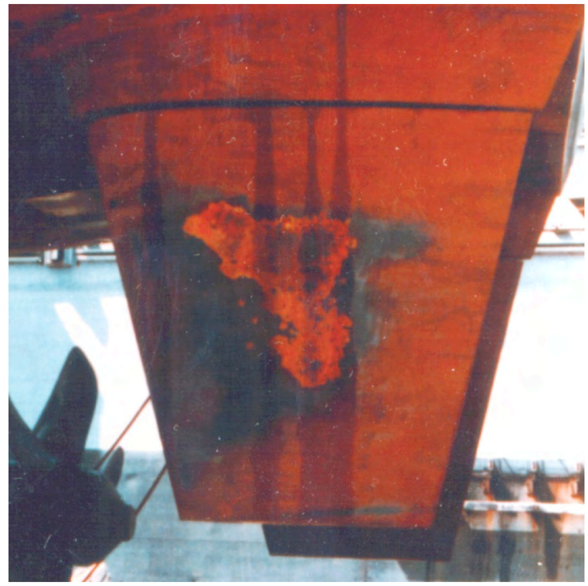

Fig. 13. Cavitation erosion damage on ARLEIGH BURKE (DDG 51) port rudder

The twisted rudder was tested on the DDG 51 model in the LCC. The original design (non-twisted) rudder was tested as well to confirm the cavitation patterns seen in drydock inspections and full scale viewing trials, and to provide comparison to the new rudder. The measurements included rudder surface pressures, side forces, drag, cavitation inception angles, cavitation inception speeds and noise levels. At model-scale, the twisted rudder exhibited a reduction the occurrence and amount of erosive surface cavitation, and the results are detailed in Ref. 1.

USS BULKELEY (DDG 84) was fitted with a pair of twisted rudders in 2001, Fig. 14. Cavitation, powering, fuel efficiency, vibration, noise, and maneuvering trials were conducted and evaluated for the BULKELEY with twisted rudders using the OSCAR AUSTIN (DDG 79) with fleet rudders as a baseline, Krueger et. al.[9]

The twisted rudder cavitation viewing on BULKELEY showed significant improvement over the fleet rudder. The cavitation inception envelope showed improvements similar to that established at model-scale. In addition, the installation of the rudder tip device appears to mitigate steady state tip cavitation under most normal loading conditions. The twisted rudder design is scheduled for installation on the remaining Flight IIA hulls beginning with DDG 103 and continuing through DDG 122.

[9] NSWCCD Code 50 report of limited distribution.

Fig. 14. Twisted rudder on BULKELEY (DDG 84)

A further reduction in cavitation on DDG 51 fleet rudders could be accomplished with a redesign of the rudder shoe. Subsequent to the contract design completed at NSWCCD, the width and length of the DDG 51 rudder shoe was increased to accommodate the rudder bearing. In the current fleet design, there is a mismatch in the interface between the top of the rudder (rudder root) and the bottom face of the rudder shoe. For the prevention of gap cavitation at the rudder root, this rudder-shoe interface should be modified in order to eliminate the existing offset.

Shaftline support strut cavitation has also become a maintenance issue on the DDG 51 Class, as well as the source of noise and flow unsteadiness into the propeller. The outboard struts of the main strut barrel cavitate at high speeds. In the LCC, it was shown that an alignment correction of 3 degrees trailing edge outboard eliminated the cavitation on the lower half of the strut up to the full power point. The proposed alignment correction was not implemented due to budget cuts. The design change is ready to be installed and tested on the next available DDG. There is also a small area of cavitation at top of strut, which has been exhibited on some of the DDGs. This situation has not yet been addressed.

HULL AND PROPELLER CLEANING

The cleaning of biofouling off the hull and propeller is an important practice in maintaining good ship performance. Current U.S. Navy practice is to inspect its ships at regular intervals, and as determined necessary, perform a full cleaning (hull, propeller, rudder, shafts and struts) or an interim cleaning (propeller, rudder, shafts and struts).

Biofouling is the natural process of the attachment and growth of marine organisms on the underwater surfaces of a ship. Biofouling of the ship increases the power required to maintain speed, resulting in a loss of fuel economy. On the propellers, biofouling can also cause an increase in noise, vibrations, and cavitation. The severity of biofouling is generally greater on unpainted surfaces such as the propellers, as well as on the hull, struts and rudders in areas where the paint coating has become degraded.

In 1991, a U.S. Navy study of hull biofouling at the time of hull cleaning showed that 61 percent of the ships were above a Fouling Rating (FR) of 50 over 20 percent of the hull surface, at that time the Navy's threshold for cleaning, Hundley.[10] The current threshold, FR 40 over 20 percent, has been shown to result in a 12-18% increase in power.[10] Sea trials conducted during a long-term evaluation on the USS WHIPPLE (FF 1062), showed that by 800 days out of drydock the biofouling had caused an astounding 110 percent increase in power at a speed of 17.4 knots.[10]

It has been determined that at a Rubert Scale propeller roughness rating of F (highest rating) the powering performance of the DDG 51 propeller is degraded by 6.8 percent, Jessup.[11] The rating of F represents a mean roughness height of 30 microns (0.003 inch), perhaps equivalent to a barely perceivable 'orange peel' level of biofouling. Heavy slime and incipient calcareous growth on a propeller can cause a 9 to 11 percent increase in power, Black and Swithenbank.[12] However, severe biofouling of the propellers, as well as on the hull, struts and rudders in areas where the paint coating has become degraded, such as that depicted on STOCKDALE (DDG 106), Fig. 15, is not uncommon on U.S. Navy ships.

[10] NSWCCD Code 50 report of limited distribution.
[11] NSWCCD Code 50 report of limited distribution.
[12] NSWCCD Code 50 report of limited distribution.

Fig. 15. Severe biofouling on STOCKDALE (DDG 106)

Cleaning of the hull and propellers has the potential for fuel cost avoidance far in excess of the potential of any appendage addition. The degree and amount of fuel cost avoidance possible due to hull and propeller cleaning is highly variable and dependant on many factors, such as: adherence to the schedule of fouling inspections, completion of full or interim cleanings, ship operations, time spent underway or pierside, and ship deployment locations. Implementation of the following ideas and technologies could reduce the excess fuel consumption caused by biofouling.

- Onboard, automated propeller cleaning system
- Adoption of a condition-based cleaning policy

In addition, the degree of biofouling may be to some extent controlled with the use of advanced hull and propeller coatings. The topic of biofouling control will not be addressed in this document.

An onboard, automated propeller cleaning system would reduce the amount of biofouling on the propeller. Such a system would be stored on board and be able to be deployed by the crew for a monthly cleaning of the propellers. Deployment of such a technology for regular propeller cleanings could save approximately 734 bbls of fuel, or $128K, per ship, per year, Black and Swithenbank.[12]

Adoption of a condition-based cleaning policy would imply that the hull and propeller cleanings would be completed when indicated by the ship hydrodynamic performance, rather than on a fixed schedule. Several onboard ship self-monitoring methods, using both the ship's force personnel and automated systems, have been employed by the U.S. Navy with varying degrees of success. At minimum, all methods are dependent on the accurate measurement of three core parameters obtained from the ship's resident equipment, ship speed, shaft torque, and shaft rotational speed. This data is then used to calculate a ship performance indicator, expressed by a specified relationship between total delivered power and ship speed-through-the-water. The required power at speed is known to increase as a result of biofouling. Thus, the ship's force can independently determine when the degree of fouling increases their power versus speed relationship beyond a pre-determined threshold for hull and propeller cleaning.

A prototype self-assessment procedure, utilizing ship's instrumentation and force personnel, was developed and tested on three U.S. Navy combatants in 1996-97, Hundley.[10] At that time, it was determined that the ship's instrumentation was capable of providing measurements to the accuracy required by the self-assessment procedure. However, requirements for the utilization of ship's force proved somewhat unreliable, and the repeated reciprocal runs required to determine speed-through-the-water precluded the usage of the assessment on a routine basis. This prompted the pursuit of an automated system to minimize the effort on the part of the ship's force, and for instrumentation capable of directly measuring speed-through-the-water to eliminate the reciprocal run requirement.

The basic goals of the current Ship Propulsion Condition Monitor (SPCM) was to make ship performance self-assessment completely transparent to the ship's force, and to insure that the ship would have no operational or maintenance requirements for the system. NSWCCD developed the computer system within SPCM that calculates the additional fuel spent on propulsion to overcome increased skin friction due to biofouling. SPCM prototypes are installed and operating aboard USS COLE (DDG 67), USS GONZALEZ (DDG 66), USS PORT ROYAL (CG 73), and USS BUNKER HILL (CG52). Connected to electronic sensors aboard each ship, engineering data such as shaft torque and RPM, navigational data such as ship speed and GPS information, and environmental variables such as wind speed and direction are monitored and recorded. If a time period is found that meets the pre-defined environmental and engineering conditions, the SPCM data is then used to calculate the performance indicators for comparison to the clean-hull performance baselines.

The prototype SPCM systems fell short of their goals due to the limitations of the ships' installed instrumentation. The CG installations were more dependable, partly because they relied heavily upon NSWCCD instrumentation, and partly because they were the last ones installed, so some lessons learned on earlier installations were incorporated. The DDG installations depended entirely upon ship data systems, and normal maintenance and upgrades unintentionally disabled one or more of the critical data streams on several occasions.

SPCM performance was also hampered by the lack of accuracy in the input parameter of ship speed-through-the-water as measured by the ship's electro-magnetic speed sensor (EM Log). Speed-through-the-water can be directly and accurately measured with sensors such as DSVL (Doppler Sonar Velocity Log) and ADCP (Acoustic Doppler Current Profiler). However, previous efforts towards deploying these sensors have been hampered with retrofit requirements involving limited sensor location and installation using existing through-hull fittings. Future efforts will be focused on the development of modified through-hull apparatuses.

SUMMARY / CONCLUSIONS

As of this writing, the U.S. Navy is in the process of building and activating 10 additional DDG 79 Class Flight IIA destroyers (DDG 113-122), and current plans call for the acquisition of as many as 24 Flight III ships beyond that. This brings the current scheduled total number of DDG 51 Class destroyers to 72, with plans for over 90. It would be highly desirable for the new ships to adopt many of the hydrodynamic design efforts discussed in this paper, and for the design changes to be retrofit to existing ships where they are economically feasible. Many of the design changes will pay for their installation through savings in fuel and maintenance.

It is important to bear in mind that even a relatively moderate fuel cost savings of $300K per ship (approximately 3%) represents a very significant total ownership cost savings of $735 Million when applied over a minimum of 70 ships and 35-year service life. This is why it is relevant to focus on relatively small percentage fuel savings per ship.

Readjusting the stern flap angle and chord for the heavier ship condition and new operational profile is also just a minor effort and the costs are expected to be recouped through fuel savings.

The upfront additional design costs and slight increase in propeller cost of the 18 ft Diameter propeller is also expected to repay itself through fuel savings in just a few years.

The Retrofit Bow Bulb installation costs would also be recouped through fuel savings in just a few years. However, this concept will need additional risk mitigation work regarding the acoustics and structural aspects.

The Stern End Bulb is still a design in progress. It may be beneficial to adopt the SEB and the Retrofit Bow Bulb together in order to fine tune the resulting maneuvering impacts.

The development of an accurate propeller pitch sensor, and the development of better hull and propeller cleaning strategies, will have fuel savings benefits for new construction and retrofit DDG 51s and for other USN ships, and thus, it will have a large impact.

Correcting the mismatch between the rudder and the rudder shoe, and correcting the support strut twist angle, are expected to incur just very small costs that will be recouped through maintenance savings.

The contra-rotating propeller information is offered mostly to provide an option in case fuel prices soar significantly beyond current levels, and in case additional hydrodynamic benefits are being sought.

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NOMENCLATURE

ADCP Acoustic Doppler Current Profiler
ATD Advanced Technology Demonstration
Bbls Barrels
CFD Computational Fluid Dynamics
CG Guided Missile Cruiser
CR Contra-Rotation propeller
CRP Controllable-Reversible Pitch propeller
DDG Guided Missile Destroyer
DSVL Doppler Sonar Velocity Log
DTMB David Taylor Model Basin
EM Log Electro-Magnetic speed sensor
ETA_D Propulsive Coefficient, delivered efficiency
FEM Fuel-Efficient Mode
FF Fast Frigate
FP Fixed Pitch propeller
FR Fouling Rating
FRR&DP Fleet Readiness Research & Development Program
ft feet (length)
FY Fiscal Year
IAR Independent Applied Research
LCC Large Cavitation Channel
m meter (length)
NAVSEA Naval Sea Systems Command
NEURS Navy Energy Usage Reporting System
NSWCCD Naval Surface Warfare Center Carderock Division
ONR Office of Naval Research
PCM Program Control Module
R&D Research and Development
S&T Science and Technology
SEB Stern End Bulb
SPCM Ship Propulsion Condition Monitor
SS# Sea State Number in rough water
TOC Total Ownership Costs
USCG U.S. Coast Guard
USN U.S. Navy
$K multiple of $1000

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AUTHOR BIOGRAPHIES

Dominic S. Cusanelli is a Senior Engineer / Naval Architect at NSWCCD, where he has been employed since 1984. He has been the Principal Engineer and Project Manager for a large variety of model-scale R&D programs and full-scale ship trials, including all of the U.S. Navy and Coast Guard stern flap programs. He received his Bachelor of Engineering degree in Ocean Engineering and Naval Architecture from Stevens Institute of Technology, Hoboken, NJ, in 1984. He has been awarded six U.S. patents for advances in ship design and has won six national awards for ship design, fuel savings, and environmental protection.

Gabor Karafiath, is a supervisory Naval Architect at the Resistance and Propulsion Division, NSWCCD Code 5800, and has directed the design evaluation for powering on a large number of ship designs. He has worked for 39 years at NSWCCD in the area of resistance and powering for surface ships, high-speed craft, and advanced marine vehicles. He has led many energy savings efforts for USN ships. He received his combined B.S. degree in Naval Architecture and Aerospace Engineering in 1971 and his M.S. degree in Naval Architecture in 1972, both from the University of Michigan.

APPENDIX

The DDG 51 Class FY12 fuel calculation method for the determination of annual underway propulsion fuel consumption and device fuel savings is presented herein. During the preparation of this document, the authors undertook the task of re-evaluating the performances of the presented energy technologies based on this calculation method.

The DDG 51 Class average data from NEURS[1] Atlantic and Pacific fleets were combined (after the removal of ships reported as ‘incomplete data’). A yearly Class average is produced for underway hours (3134 hrs/yr) and underway fuel consumption in total bbls (76,269 bbls/yr), and fuel consumption rates (bbls/hr) underway and not underway. The not underway fuel rate (assumed to be equivalent to the hotel load) is subtracted from the underway, to determine the underway propulsion fuel rate, which is then multiplied by the underway hours to produce the Class average annual fuel consumption for propulsion

(56,420 bbls/yr). This is the baseline propulsion fuel consumption from which all energy device fuel savings are calculated.

For a calculation of Class annual total underway fuel consumption, the tabular method as set forth in 2003 by NAVSEA[13] is generally utilized. This table specifies the following:
• The Speed-Time Profile (STP) designates the percent time-at-speed/yr. At the time of this STP determination, the DDG 51 Class average underway operational hours was 2563 hrs/yr, 18% lower than it is currently.
• Three engine operating alignments are defined, (A) trail shaft, (B) 2-engine split plant, and (C) 4-engine full plant, and percent time of annual operations in each alignment is designated per speed.
• Total underway engine fuel rates-at-speed for the three engine operating alignments are designated. These fuel rates do not specify fuel consumption contributions for propulsion versus hotel loads.

Performance and Special Trials were conducted in 2001 on the USS OSCAR AUSTIN (DDG 79), Hill and Barros.[14] During the DDG 79 trials, measurements were made of ship speed, shaft power (SHP), and engine fuel rates on the propulsion engines during the three engine operating alignments, A, B, and C. The data represents engine fuel rates for propulsion only, which are directly correlated to ship speed and shaft power. Hotel loads are not included.

The following updates were made to the NAVSEA 2003 annual fuel consumption calculation tabular method for the FY12 analysis.
• STP percent time-at-speed, was applied to the FY12 NEURS reported underway operational hours (3134 hrs/yr), to produce hrs/yr at each speed in the profile.
• The DDG 51 Class standardization delivered power (SHP) as measured during the DDG 79 Performance and Special Trials was utilized as the reference power-at-speed.
• Curves of measured underway propulsion engine fuel rates vs SHP were developed for the three engine operating alignments A, B, and C, from the data of the DDG 79 Performance and Special Trials.

The DDG 51 Class FY12 annual propulsion fuel consumption calculation method then proceeds as follows:
• Full-scale power (SHP), either measured from a full-scale trial or predicted from a model-scale test, is entered for each speed in the profile.
• SHP is multiplied by hrs/yr at each speed to produce annual hP-hrs/yr at each speed. The summation for all speeds in the profile results in the total annual propulsion power, expressed as total hP-hrs/yr.
• At each speed in the profile, underway propulsion fuel consumption rates for each of the three engine operating alignments is produced by interpolation along the measured curves of underway propulsion engine fuel rates vs SHP.
• The interpolated engine fuel rates for each engine alignment is then multiplied by the resultant number of hrs/year at each of the engine alignments, produced from the weighted engine alignment time profile for each speed in the profile, producing values of barrels/yr at each speed in the profile.
• Annual underway propulsion fuel consumption is the summation of the fuel consumptions at all the speeds in the profile, expressed as total barrels/year.

This FY12 update of the NAVSEA 2003 tabular calculation method produces a value of 60,627 bbls/yr annual underway propulsion fuel consumption for a ship of the DDG 51 Class. This represents a value 6.9% higher than the Class average 56,420 bbls/yr determined from the FY12 NEURS data. In-depth analysis indicates that the NAVSEA 2003 STP and engine operating alignments require updating in the interest of accuracy in reflecting FY12 ship operations. However, the biasing due to inaccuracy in the STP and engine alignments are applied equivalently for both baseline and device fuel calculations in this method. For the final analysis, fuel reduction produced from this calculation will be applied on a percentage basis to actual reported fuel consumption data, and thus, the equivalent bias can be considered negligible to the analysis.

For each energy device or technology, the FY12 updated annual underway propulsion fuel consumption tabular calculation is repeated with the corresponding baseline SHP curve (not necessarily the Class standardization) and device-installed SHP curve. Each SHP curve produces a modification in the engine fuel rates at speed (for all three engine alignments) due to the changes in the SHP at speed, and the relationship of engine fuel rates vs SHP. A comparison between the annual propulsion fuel consumption summations of the baseline and device configurations indicates the device's annual fuel reduction performance, produced as a value of total barrels/year.

[13] NAVSEA Code 05Z1 report of limited distribution.
[14] NSWCCD Code 50 report of limited distribution.

The device's annual underway fuel reduction is then expressed as a percentage of the corresponding baseline annual propulsion fuel consumption. This percentage reduction is then applied to the actual annual propulsion fuel consumption determined from FY12 NEURS (56,420 bbls/yr) to produce the device's final annual propulsion fuel reduction in terms of barrels/year, as reported in this paper. Fuel cost savings is then derived using the standard fuel price of $175/bbl established for FY12.

Exception: For energy technologies where neither powering data nor fuel data were available to compare between device and baseline, either full-scale or model scale, the previously claimed fuel reduction potential was simply adjusted to reflect the current FY12 NEURS Class average propulsion fuel consumption of 56,420 bbls/yr, and for the standard fuel price of $175/bbl.