Approved for Public Release
Distribution is Unlimited

Dr. Norbert Doerry

Surface Ship Endurance Fuel Calculations

ABSTRACT

In October 2011, the Navy issued a revision to DDS 200-1, Calculation of Surface Ship Endurance Fuel Requirements. This revision incorporates three different endurance requirements for which the ship's tankage must be sized to meet: surge to theater, economical transit, and operational presence. These conditions represent three different operational scenarios for a ship. Economical transit minimizes the consumption of fuel under normal transits. Surge to theater requires a ship to travel a specified distance rapidly, (such as to an operational area) without having to refuel. Operational presence requires a ship while deployed to remain on station for a specified period of time. The mobility requirements of these scenarios in conjunction with sustained speed requirements can drive the choice of prime movers and their ratings. Other changes include explicit applicability to ships with Integrated Power Systems, the ability to use calculated factors instead of fixed factors, and the use of an ambient condition profile. This paper describes these and other changes to the DDS, presents the motivation for the changes, and highlights the impact these changes will have on ship design.

INTRODUCTION

Between 1982 and 2011, Design Data Sheet DDS 200-1 was used to size fuel tanks on naval ships. DDS 200-1 presents a calculation method based on a customer specified endurance range and endurance speed. Created in a time when many calculations were performed by hand or calculator, the method used in this DDS incorporated a number of simplifying assumptions. The increased use of design optimization methods in the past decade can result in ship designs that are optimized around the simplified endurance metrics instead of optimized on how the ships operate. The ability to optimize plant efficiency to specific speeds was enhanced with the introduction of Integrated Power Systems and Hybrid Electric Drive. Consequently the need to align the endurance fuel calculations with fleet operational practices became evident in the 2005 time frame.

The FY06 National Defense Authorization Act directed the Secretary of the Navy to produce a report on alternative propulsion methods. This report was submitted in January 2007 (NAVSEA 2007) and was summarized by Webster et al. (2007) It introduced the concept of using Surge to Theater and Operational Presence as mobility metrics for operational effectiveness:

Surge to Theater emulates the need for a ship to quickly transit to an operating area without having to refuel often. For the report to Congress, surge to theater was measured in the number of times a ship needed to refuel to travel 4500 nautical miles at 30 knots for surface combatants and 25 knots for amphibious warfare ships. An alternative metric of the maximum speed achievable to reach approximately 4200 miles was also employed.

The report to Congress measured Operational Presence as the number of hours a ship can remain on station while conducting missions in theater before having to go off station to refuel.

Subsequently, Doerry (2007) recommended sizing fuel tanks based on the maximum fuel requirement of up to three of the following conditions:

a. Surge to Theater: Maximum times a ship can refuel to transit a given distance (typically 4,000 to 10,000 nm) at maximum design speed at a given sea state, with only self defense capability. Refueling is assumed when 1/2 of the fuel capacity is consumed.

b. Economical Transit: Similar to the traditional endurance speed and endurance range.

c. Operational Presence: Defined as the minimum time that a ship should be capable of conducting one or more missions such that a maximum of 1/3 of the fuel capacity is consumed.

In 2010, a project to revise DDS 200-1 to incorporate these recommendations and other lessons learned was initiated. Recommendations for improvements to the DDS were received from many technical warrant holders and subject matter experts. The result of this effort was DDS 200-1 Rev 1 of October 4, 2011. This paper details most of the changes incorporated into this revision.

ENDURANCE CONDITIONS

DDS 200-1 Rev 1 incorporates the three recommended endurance conditions, but modifies their definition to simplify the analysis while still preserving the original intent. A ship must have sufficient fuel tankage to accommodate the highest fuel load required by any one of the three endurance conditions. Customers are not required to specify all three conditions, but must specify at least one. Conditions that are not specified are not used to calculate endurance fuel requirements.

SURGE TO THEATER

DDS 200-1 Rev 1 defines surge to theater in terms of the ship's sustained speed requirement and the surge to theater distance. Surge to theater distance is the minimum distance (nautical miles) which a ship can sail without replenishment and using all of its burnable fuel (excluding cargo and aviation fuel), at sustained speed, deep water, and full load displacement, with a ship service operating condition corresponding to a cruise with self defense capability. This change in definition (including consuming all the burnable fuel; not just 50%) from that proposed by Doerry (2007) was based on the desire by subject matter experts to simplify the calculations. It must be noted that an actual warship would not be expected to travel the surge to theater distance and arrive on station with fuel tanks empty. The percentage of fuel that can be consumed by a ship before refueling is an operational decision somewhat independent of the ship design. As such, using the entire burnable fuel load for optimizing ship design is appropriate, but the ship's crew should view the surge to theater distance as a theoretical limit rather than an operational planning value.

ECONOMICAL TRANSIT

DDS 200-1 Rev 1 defines economical transit in terms of an endurance speed and an economical transit distance. Economical transit distance is the minimum distance (nautical miles) which a ship can sail without replenishment and using all of its burnable fuel (excluding cargo and aviation fuel), at a specified endurance speed, deep water, and full load displacement, with a ship service operating condition corresponding to a cruise with self defense capability. If an endurance speed is not specified by the customer, than a default value of 16 knots is used. The default value is representative of the economical transit speeds actually used by the fleet.

OPERATIONAL PRESENCE

DDS 200-1 Rev 1 defines operational presence in terms of an operational presence time, a speed time profile, and the operational mission(s). Operational presence time is the minimum time in hours that a ship can conduct specified missions with a given speed-time profile, with a ship service operating condition corresponding to the specified missions, without replenishment, and using all of its burnable fuel (excluding cargo and aviation fuel). The speed time profile is expressed as a percentage of time spent at each speed. As with the surge to theater distance, the operational presence time is a theoretical limit rather than an operational planning value; one would not wait until the fuel tanks were empty before refueling.

CALCULATION MODIFICATIONS

In addition implementing three endurance conditions, a number of other changes in the way calculations are performed and assumptions made.

SEA STATE AND FOULING FACTOR

DDS 200-1 provided a fixed 10% sea state and fouling factor. This factor was to account for average bottom following over a two year period. No further information was provided as to which sea state this 10% was intended to correspond. Consequently, the ship endurance calculations did not incentivize the ship designer to incorporate better seakeeping performance or to incorporate design measures to reduce fouling. With the introduction of modern seakeeping and ship resistance in a seaway prediction algorithms, it is now possible to calculate a sea state and fouling factor early in ship design.

DDS 200-1 Rev 1 specifies using head seas in the high end of sea state 4 for calculating the sea state and fouling factor. Since sea state is not sufficient for describing the sea spectrum, an operating area should be specified or the default location of the North Pacific should be used. Wind velocities associated with the high end of sea sate 4 should also be assumed for calculating wind drag. Sea state 4 was chosen because ships will likely experience sea state 4 or less about 50% to 60% of the time in most operating areas.

To stay consistent with past practice, DDS 200-1 Rev 1 still recommends using the 10% sea state and fouling factor as a default value for early studies where there is not enough time or resources to computationally determine it. The actual value is highly dependent on sea state and hull fouling assumptions.

For many hullforms, 8-10% is a reasonable approximation for the increase in resistance in sea state 4 above that for calm water without considering the impact of hull fouling. For example see Higgins et al. [2006].

Historically, hull fouling with conventional bottom paints and periodic bottom inspection and cleaning could be approximated as increasing the resistance of the ship 1% for each month after cleaning. [Higgins et al. 2006] Hull fouling could easily result in a reduction in fuel efficiency in the amount of 5 to 12%. {Doerry et al. 2010] More recently in an effort to reduce fuel consumption, fleet practice has been to keep the hull and propulsors as clean as possible through the use of advanced coatings such as ablative paint systems and frequent underwater inspections and cleaning. These practices have significantly reduced the contribution of fouling to the sea state and fouling factor. With these practices, assuming 2 to 4% for hull fouling is likely reasonable.

Hence while the default value (10%) for the sea state and fouling factor is achievable, it is likely not conservative (it likely never was conservative). Whenever possible, the ship designer should use the best data available to improve the estimate for this factor.

AMBIENT CONDITION PROFILE

DDS 200-1 specified a single ambient condition of 100º F and 40 percent relative humidity. Because fuel consumption on modern ships is strongly influenced by temperature, DDS 200-1 rev 1 allows for using an ambient condition profile and provides a default profile of:

> 25% of the time at 10º F with 95% relative humidity
>
> 50% of the time at 59º F with 95% relative humidity
>
> 25% of the time at 100º F with 40% relative humidity

This new profile is intended to drive to balanced power system designs that are fuel efficient across the expected temperature profile. Customers are empowered to specify an alternate profile.

CONVERSION TO METRIC UNITS

DDS 200-1 Rev 1 converts all units of measurement to the metric system (International System of Units: SI) with the exception of Fahrenheit, nautical miles, knots, and hours. Degrees Fahrenheit were retained in favor of degrees Kelvin (or Celsius) to maintain compatibility with other standards. Nautical miles and knots are non-SI units that are recognized by SI as used by special interest groups such as the maritime industry. Hours are non-SI units accepted for use with the International System of Units. (BIPM 2006)

24 HOUR AVERAGE ELECTRIC LOAD

DDS 200-1 did not specify the ships operating condition for calculating the 24 hour average electric load. The method for calculating the 24 hour average load was described in (NAVSEA 1992), and it was not clear to which operational condition it was meant to correspond. In the past, fuel consumption for ship service power was considerably lower than that for propulsion, hence inaccuracy in its estimation did not necessarily impact the required endurance fuel. With the growth of electric loads, it is now possible that the ship service fuel requirements may be greater than the propulsion fuel requirements for the economical transit and operational presence conditions. Hence more fidelity in modeling 24 hour average electric load is needed.

DDS 200-1 Rev 1 specifies using electric loads corresponding to cruise with self defense capability (Condition III Wartime Cruising for surface combatants) for the economical transit and surge to theater calculations. DDS 200-1 Rev 1 also specifies using electric loads corresponding to applicable ship missions for the operational presence calculations. Furthermore, DDS 200-1 Rev 1 states that the electric loads should have margin and service life allowances applied.

An ongoing update to DDS 310-1 will provide additional guidance for calculating the 24 hour average loads for the different operating conditions.

INSTRUMENTATION INACCURACY CORRECTION FACTOR

DDS 200-1 included a correction factor of between 1.02 and 1.04 to account for instrumentation inaccuracy during ship acceptance trials, and for minor machinery design changes made during the construction period. Discussions with Technical Warrant Holders and Subject Matter Experts indicated that a logical basis for inclusion of this correction factor no longer exists. Consequently, DDS 200-1 Rev 1 removes this correction factor.

TANK VOLUME

DDS 200-1 states an additional 5% tank volume over that needed for the endurance fuel load is required to account for fuel expansion. DDS 200-1 Rev 1 also reminds the designer to account for internal structure (typically 2 percent). DDS 200-1 Rev 1 also clarifies that the endurance fuel load does not include fuel required for the operation of aircraft, boats, other vehicles, or carried as cargo. These modifications were made based on lessons learned on recent ship designs and guidance from the applicable Technical Warrant Holders.

CALCULATION EXAMPLES

DDS 200-1 included a “Surface Ship Endurance Calculation Form” to aid in the manual calculation of endurance fuel requirements. DDS 200-1 Rev 1 recognizes that forms for manual calculation will likely not be used in the future. Instead two examples, called use cases, are worked out to illustrate the calculation methods. The first is for a traditional mechanical drive configuration, and the second is for an integrated power system configuration.

SPECIAL CASES

Recent experience with high speed ships (JHSV and LCS for example) and ships with hybrid electric drive (LHD 8 and DDG 51) have highlighted issues that are not addressed in DDS 200-1.

HIGH SPEED SHIPS

DDS 200-1 rev 1 recognizes that:

"The propulsion speed power curve for many high speed ships (particularly those with uncompensated fuel systems) are very sensitive to displacement in that as fuel is burned, displacement and drag can be significantly reduced. In these cases, assuming full load displacement for the economical transit burnable fuel load and surge to theater burnable fuel load cases is highly conservative. In these cases the procedure for calculating the economical transit burnable fuel load and surge to theater burnable fuel load may be modified to account for the reduction in ship drag as fuel is consumed. However, since the Navy typically does not allow ships to come close to burning all of its available fuel, the ship should be able to achieve half of its economical transit distance while expending no more than half of its design burnable fuel load. Likewise, the ship should be able to achieve half of its surge to theater distance while expending no more than half of its design burnable fuel load. The operational presence burnable fuel load calculations should continue to use full load displacement."

DDS 200-1 provides two methods to calculate the economical transit and surge to theater burnable fuel loads for this special case.

ECONOMICAL TRANSIT SPEED MODIFICATIONS

As stated in DDS 200-1 rev1:

"Some ships may be able to traverse the economical transit distance using less fuel with a speed greater than the specified endurance speed. With customer approval, a more optimal speed above the endurance speed may be used for the economical transit burnable fuel calculations."

This condition could happen for vessels that have one or more "hump" speeds characterized by a region of negative slope in their speed power curve. Planing hulls and some multi-hull vessels can have this speed power characteristic.

DDS 200-1 Rev 1 goes on to state:

"Ships potentially may be able to achieve the stated endurance speed on average using less fuel by using a speed time profile where a portion of the time is spent above the endurance speed and a portion of the time is spent below the endurance speed. With customer approval, a speed, percent time profile that results in an average speed equal to or greater than the endurance speed, may be used for the economical transit burnable fuel calculations if it results in a smaller economical transit burnable fuel load."

This condition is possible in combined plants and hybrid plants where a low power prime mover/propulsion system is not sufficient to achieve the stated endurance speed, but is considerably more fuel efficient than the high power prime mover/propulsion plant.

SHIP DESIGN IMPLICATIONS

For many ships, fuel storage contributes significantly to full load displacement. Fuel consumption is also a significant driver for total ownership cost. Hence the ship designer is usually incentivized to minimize the endurance fuel load. The changes reflected in DDS 200-1 rev 1 will likely influence the way the power system is optimized and in the way the hull is optimized.

POWER SYSTEM OPTIMIZATION

Historically, the power system designer would select the propulsion plant primarily on being able to achieve the sustained speed at minimum cost. Optimizing fuel efficiency at the endurance speed typically was a secondary consideration. The introduction of integrated power systems and hybrid plants however, greatly enhanced the ability of the power system designer to tune the power system design for optimal performance at the endurance speed.

DDS 200-1 rev 1 now incentivizes the power system designer to produce power system designs that are balanced for the different operational conditions the ship will experience. The increased use of cruise-boost (including hybrid electric drive) and integrated power systems is a likely outcome.

Because the endurance requirements are now stated in a manner more aligned with how the ships operate, an indirect result of minimizing fuel tankage needs to meet the endurance requirements as stated in DDS 200-1 rev 1 will likely be a reduction in annual fuel consumption as compared to a ship designed under DDS 200-1.

HULL RESISTANCE OPTIMIZATION IN HIGHER SEA STATES

Historically, hull designs were often optimized to minimize resistance in calm water. Little attention was paid to minimizing drag in higher sea states because none of the metrics used to evaluate a ship design depended on the actual hull resistance in anything other than calm water. DDS 200-1 rev 1 will now incentivize the hull designer to consider hull resistance in sea states the operator is much more likely to encounter operationally. Time will tell how this is manifested in the shape of future hulls and appendages.

DESIGN TOOLS

SYNTHESIS TOOLS

The Navy's primary design synthesis tool for concept studies is the Advanced Surface Ship and Submarine Evaluation Tool (ASSET). ASSET is currently being rearchitected and integrated in a broader Rapid Design and Integration (RDI) environment under the Computational Research and Engineering Acquisition Tools and Environments (CREATE) program. While ASSET currently does not directly support the methods in DDS 200-1 Rev 1, RDI enables the integration of the appropriate ship resistance and endurance programs into the overall ship synthesis loop. Changes to the Leading Edge Architecture for Prototyping Systems (LEAPS) which underlies ASSET and the CREATE tools may also be required to capture the additional endurance fuel data.

SHIP RESISTANCE PREDICTION IN HIGHER SEA STATES

The Integrated Hydrodynamics Design Environment (IHDE) is being incrementally developed under the CREATE program. IHDE enables advanced hydrodynamic analysis codes to be used in early concept exploration by naval architects. It interacts directly with LEAPS for concept geometry for storing analysis results. IHDE version 2.0 has been released and incorporated the Ships Motions Program (SMP) IHDE plans for a roughly annual version release schedule. Each version of IHDE will add greater functionality.

For more detailed analysis in later stages of design, the Navy is developing NavyFOAM under the CREATE program. NavyFOAM incorporates Navy specific features to the open source Computational Fluid Dynamics (CFD) program OpenFOAM. Access to NavyFOAM V1.0 is starting to be granted for use on US Government projects (code is not being distributed)

ELECTRIC LOAD ANALYSIS

Electric Load Analysis is typically performed parametrically or by spreadsheet tabulation and roll-up. ASSET contains parametric algorithms which require updating to reflect changes in electrical loads since the algorithms were developed and to reflect changes in the definitions for the operating conditions for calculating endurance fuel requirements. Similarly, most ship design organizations have created their own sets of spreadsheets for conducting electrical load analysis. These spreadsheets will require revision to produce the electrical loads needed for DDS 200-1 rev 1.

FUTURE WORK

To fully implement the new procedures described in DDS 200-1 rev 1, the following actions still remain:

a. Incorporate DDS 200-1 rev 1 into design rules and specifications (planned for 2012)

b. Revise DDS 310-1 to include calculations for 24 hour averages (ongoing)

c. Revise the NAVSEA Design Practices and Criteria Manual, Electrical Systems Chapter 300 to reflect the updated methods in DDS 200-1 rev 1. (planned for 2012)

d. Update ASSET / RDI / LEAPS to include new calculation methods and associated data. (not yet funded)

CONCLUSION

DDS 200-1 Rev 1 is a significant revision to better align our ship design practices with how the fleet actually operates. Over time, it will likely influence the way the Navy optimizes its power and propulsion systems as well as the hydrodynamic shape of hulls and appendages. Tools and associated rules and standards will be revised to incorporate these new methods.

DDS 200-1 Rev 1 is available online from the Defense Technical Information Center at http://www.dtic.mil/dtic/tr/fulltext/u2/a550279.pdf

REFERENCES

BIPM (International Bureau of Weights and Measures), "The International System of Units (SI)," 8th Edition, 2006.

Doerry, CAPT Norbert H , "Sizing Power Generation and Fuel Capacity of the All-Electric Warship" presented at IEEE ESTS 2007, Arlington, VA, May 22-23, 2007

Doerry, Norbert H., Timothy J. McCoy, and Thomas W. Martin, "Energy and the affordable future fleet ," Presented at the 10th International Naval Engineering Conference and Exhibition (INEC 2010), Portsmouth, UK, May 11-13, 2010.

FY06 National Defense Authorization Act, House Resolution 109-360, section 130.

Higgins, Chris, Mike Holland, and Tom Martin, "DD(X) High-Speed Performance," TCC-121300-CDIT Trade Studies - Speed, May 30, 2006.

Naval Sea Systems Command, "Design Data Sheet: Calculation of Surface Ship Endurance Fuel Requirements," DDS 200-1 Rev 1 of October 4, 2011

Naval Sea Systems Command, "Design Data Sheet: Calculation of Surface Ship Endurance Fuel Requirements," DDS 200-1 of March 1, 1982

Naval Sea Systems Command, "Design Data Sheet: Electrical System Load and Power Analysis for Surface Ships," DDS 310-1 of 1 July 1980.

Naval Sea Systems Command, “Design Practice and Criteria Manual, Electrical Systems for Surface ships, Chapter 300,” NAVSEA T9300-AF-PRO-020 approved 31 Dec 1992.

Naval Sea Systems Command, "Report to Congress on Alternative Propulsion Methods for Surface Combatants and Amphibious Warfare Ships," January 2007.

NAVSEA Design Practices And Criteria Manual, Electrical Systems For Surface Ships, Chapter 300, NAVSEA T9300-AFPRO-020.

Webster, James S., Howard Fireman, Dillon A. Allen, Adrian J. MacKenna, and John C. Hootman, "Alternative Propulsion Methods for Surface Combatants and Amphibious Warfare Ships," 2007 SNAME Maritime Technology Conference & Exposition and Ship Production Symposium (SMTC&E/SPS), Fort Lauderdale, FL.

ACKNOWLEDGEMENTS

The author thanks the many individuals that contributed to and reviewed DDS 200-1 rev 1. Its successful completion is a tribute to the excellent contributions and feedback received from so many.

Dr. Norbert Doerry is the Technical Director of the NAVSEA SEA 05 Technology Office. He retired in 2009 as a Captain in the U.S. Navy with 26 years of commissioned service, 23 years as an Engineering Duty Officer. In his final billet, he served for nearly six years as the Technical Director for Surface Ship Design. Dr Doerry is a 1983 graduate of the United States Naval Academy and a 1991 graduate of MIT. He is the 2008 recipient of the ASNE Gold Medal. He is a member of ASNE, SNAME, IEEE and the Naval Institute and has published over 30 technical papers and technical reports.